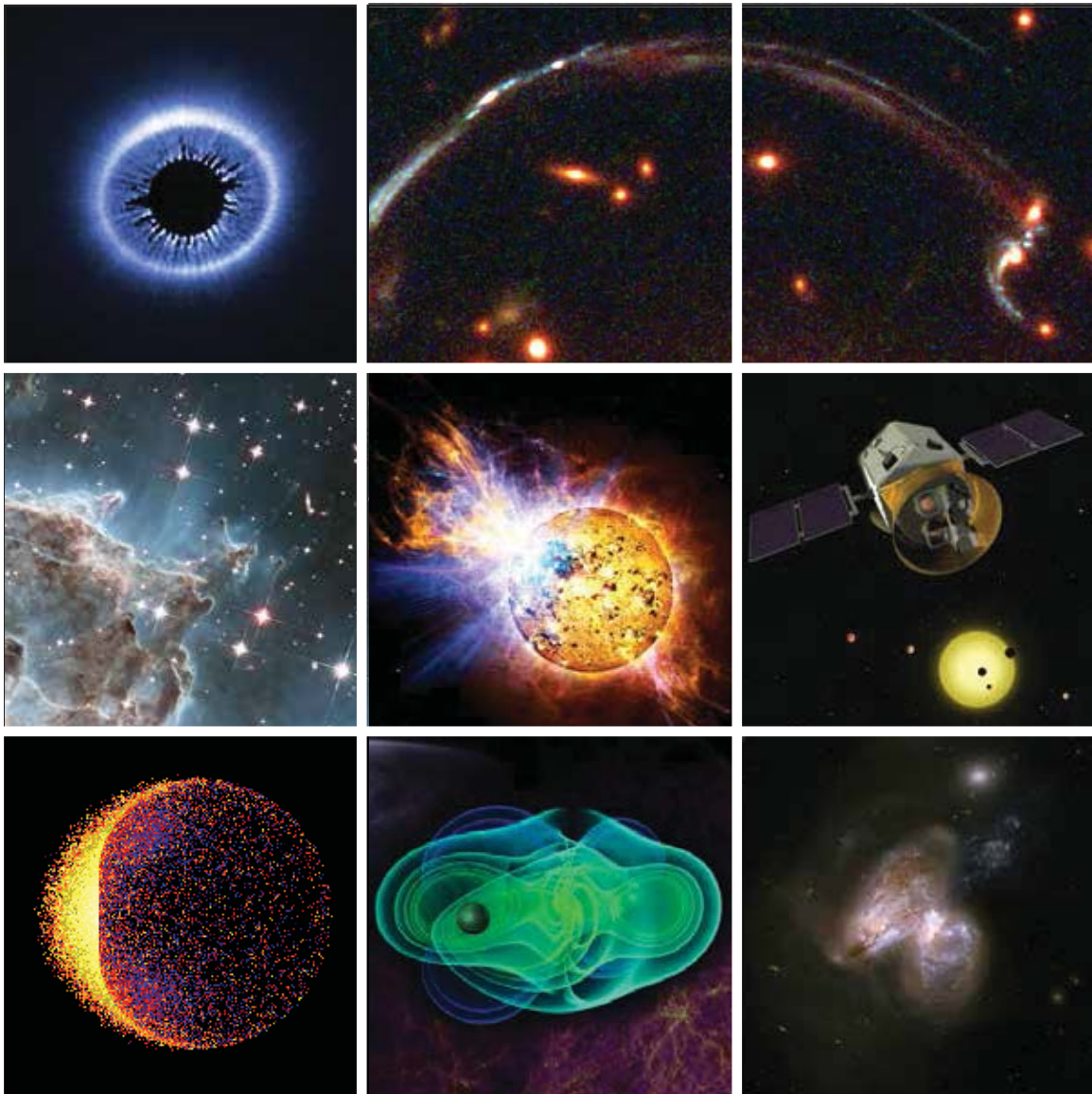




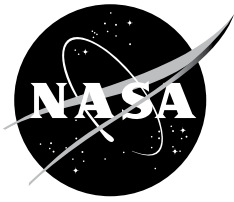
Goddard's Astrophysics Science Division Annual Report 2014

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Pat Tyler, Graphical Editor



NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

June 2015



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June 2015

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Astrophysics Science Division



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Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Frank Marshall	Gamma-ray bursts, pulsars	Swift HEASARC NuSTAR	Co-investigator; Science Center Lead NuSTAR Archive Scientist
Thomas McGlynn	X-ray and gamma-ray astronomy, interoperability, tools and techniques for astronomical research	HEASARC VAO	Archive Scientist Operations Lead NAVO Project Scientist
William Pence	X-ray astronomy of normal galaxies, data compression, advanced data analysis techniques	HEASARC	Emeritus

INTRODUCTION

The Astrophysics Science Division (ASD, Code 660) is one of the world's largest and most diverse astronomical organizations. Space flight missions are conceived, built and launched to observe the entire range of the electromagnetic spectrum, from gamma rays to centimeter waves. In addition, experiments are flown to gather data on high-energy cosmic rays, and plans are being made to detect gravitational radiation from space-borne missions. To enable these missions, we have vigorous programs of instrument and detector

development. Division scientists also carry out preparatory theoretical work and subsequent data analysis and modeling. In addition to space flight missions, we have a vibrant suborbital program with numerous sounding rocket and balloon payloads in development or operation.

The ASD is organized into five labs: the Astroparticle Physics Lab, the X-ray Astrophysics Lab, the Gravitational Astrophysics Lab, the Observational Cosmology Lab, and the Exoplanets and Stellar Astrophysics Lab. The High Energy Astrophysics Science Archive Research Center (HEASARC) is an Office at the Division level. Approximately 400 scientists and engineers work in ASD. Of these, 80 are civil servant scientists, while the rest are resident university-based scientists, contractors, postdoctoral fellows, graduate students, and administrative staff.

We currently operate the Swift Explorer mission and the Fermi Gamma-ray Space Telescope. In addition, we provide data archiving and operational support for the XMM mission (jointly with ESA) and the Suzaku mission (with JAXA). We are also a partner with Caltech on the NuSTAR mission. The Hubble Space Telescope Project is headquartered at Goddard, and ASD provides Project Scientists to oversee operations at the Space Telescope Science Institute. Projects in development include the Neutron Interior Composition Explorer (NICER) mission, an X-ray timing experiment for the International Space Station; the Transiting Exoplanet Sky Survey (TESS) Explorer mission, in collaboration with MIT (Ricker, PI); the Soft X-ray Spectrometer (SXS) for the Astro-H mission in collaboration with JAXA, and the James Webb Space Telescope (JWST).

The Wide-Field Infrared Survey Telescope (WFIRST), the highest ranked mission in the 2010 decadal survey, is in a pre-phase A study, and we are supplying study scientists for that mission.

2014 YEAR IN REVIEW

The Astrophysics Science Division (ASD) had a significant presence at the 223rd AAS meeting in January 2014. Alice Harding presented the Rossi Prize lecture “The Amazing Pulsar Machine.” She shared the prize with Dr. Roger Romani (Stanford). The Neutron Interior Composition Explorer (NICER) team had a booth presentation, and a special session “NICER: Future X-ray Astrophysics from the ISS” with talks about NICER science by Zaven Arzoumanian and Tod Strohmayer. Jon Gardner and Amber Straughn organized and led tours of the James Webb Space Telescope (JWST) facilities at GSFC for 300 AAS attendees. Projects in our Division presented two press briefings at the meeting; Fermi discussed the first gamma-ray study of a gravitational lens, and the Swift team presented results on the X-rays from the massive black hole in the galactic center.

Projects in the ASD received the results of the Senior Review of Operating Missions on May 15. In the small and medium mission category, Swift, NuSTAR, XMM and Fermi ranked highly, and will receive continued support through FY16. These missions will be invited back to the Senior Review in two years. Support for the Suzaku mission will also continue through FY16, but NASA funding will terminate after one year of Astro-H operations. In the large mission category, Hubble Space Telescope received a glowing report from the Senior Review, and a planning budget from HQ for the next five years.

The National Research Council released its report, “Evaluation of the Implementation of WFIRST in the Context of *New Worlds, New Horizons* in Astronomy and Astrophysics” in April 2014. The report was very positive overall and stated “The opportunity to increase the telescope aperture and resolution by employing the 2.4-m AFTA mirror will significantly enhance the scientific power of the mission, primarily for cosmology and general survey science, and will also positively impact the exoplanet microlensing survey. WFIRST/AFTA’s planned observing program is responsive to all the scientific goals describe in NWNH.” This was tempered with some cautionary warnings about the added risks due to using inherited hardware and the low technology readiness level of the coronagraph. Neil Gehrels, NASA Project Study Scientist for WFIRST, and David Spergel (Princeton) provided presentations to the NRC.

HAWC+, our project to provide new large format detectors for SOFIA’s HAWC instrument, held its Critical Design Review at JPL on Jan. 14-15. Johannes Staguhn (JHU/GSFC), Steve Maher, Ed Wollack and Dominic Benford participated and presented major portions of the review material. HAWC+ passed its CDR, and late in 2014 the team had produced the first flight-like detector array. Initial results show that the superconducting bolometer array yields around 1,000 operational pixels, and further measurements to demonstrate meeting flight specifications are underway.

The JWST project continues to make good progress and has maintained its schedule. The Integrated Science Instrument Module entered into a major cryo-vacuum test beginning on June 17. Randy Kimble supported the test in his role as JWST I&T Project Scientist. The cryo-vacuum test was very successful and ended in October, after a total duration of >110 days.

The Neutron Interior Composition Explorer (NICER) passed KCP-C in February and passed CDR in September. Also in 2014, the team passed an ISS Safety Review. Flight detectors and mirrors have been delivered and are undergoing testing. With minor hiccups here and there, the project is moving ahead smoothly for launch in fall 2016.

The Goddard Astro-H/SXS team has successfully completed several major milestones. All of the NASA/GSFC hardware for the SXS dewar was delivered to Japan and installed. The final step was installing the aperture assembly, including the extremely fragile thin-film blocking filters. The operation was conducted by Caroline Kilbourne, Sam Moseley, John Kazeva, and Richard Kelley, and went extremely smoothly. Late in the year, the SXS instrument had completed initial testing in Niihama, Japan, and was transported to the Tsukuba Space Center, where it will undergo a series of environmental tests through January 2015. The two flight electronics boxes provided by Goddard have been completed and are in the final stages of testing prior to delivery. Spacecraft integration of the SXS and electronics boxes will take place in late January/early February 2015.

The Visiting Committee for the Astrophysics Science Division met at Goddard on June 16-17 to review the research activities, environment and community support of the Division. The VC met with Division management, lab chiefs, research scientists, project scientists and postdocs, toured our instrument labs, and heard science talks on some of our research. The members of the VC were: Dr. Heidi Hammel (AURA; chair), Dr. Josh Grindlay (Harvard), and Dr. Dan McCommon (University of Wisconsin). We certainly ap-

precipitate the time and effort expended by the committee to provide us with feedback on our Division's activities and progress.

Ira Thorpe worked throughout the year with the LISA Pathfinder (LPF) team in Europe to prepare for science and engineering activities after launch in fall 2015. Thorpe and Slutsky (NASA postdoc) will lead U.S. participation in the operation and data analysis for the European LISA Technology Package, a flight demonstration of gravitational wave detection technology. They will also support the operations of NASA's ST7 payload on LPF.

The first results from the Diffuse X-ray emission from the Local Galaxy (DXL) sounding rocket experiment were published this year. A Nature paper by Galeazzi et al. demonstrates that the solar system is, in fact, immersed in a very diffuse bubble of million degree gas. An ApJ Letter (Snowden et al.) synthesizes data from DXL, ROSAT, and Voyager to show that the very local interstellar clouds that surround our solar system are in pressure equilibrium with the larger diffuse bubble of hot gas. These seminal results were obtained from 5 minutes of observation on a sounding rocket!

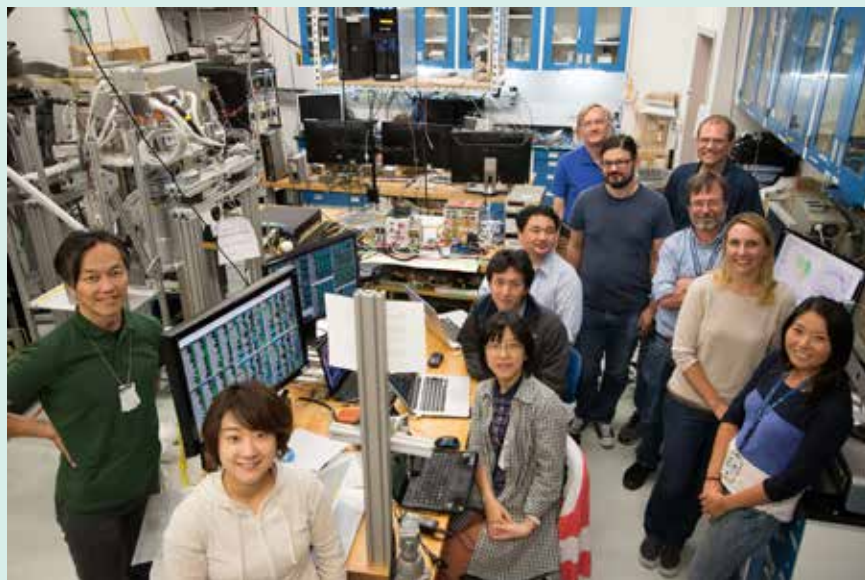
GSFC scientists include Scott Porter, Steve Snowden, Meng Chiao, Nick Thomas from ASD, Mike Collier from Solar System Division, and Brian Walsh and Dave Sibeck from Heliophysics. The PI for the DXL experiment is Massimiliano Galeazzi at the University of Miami, who was also once a post-doc at GSFC.

Sadly, we note the passing of Bruce Woodgate on April 28, 2014. Bruce had a remarkable career, spanning nearly 40 years as a civil servant at Goddard, during which he published 188 scientific and technical journal papers that have over 5300 citations. Bruce was probably best known as the PI for the Space Telescope Imaging Spectrograph (STIS) for the Hubble Space Telescope. He retired recently but continued working on UV detectors at Goddard as an Emeritus scientist. He was a mentor to many of our younger scientists and a true colleague of all. He will be sorely missed.

There are many more activities happening in ASD than can be mentioned here, but most of them are described in the rest of this document. Please read on!

Dr. William R. Oegerle
Director, Astrophysics Science Division

PHOTOS



In July 2014, the Astro-H/SXS hardware and calibration team performed end-to-end data processing with the flight spare detector system, breadboard XBOX, and EM Pulse Shape Processor. From left: Makoto Tashiro (Saitama Univ.), Saori Konami (Tokyo Metropolitan Univ.), Sawako Takeda (Saitama Univ.), Shinya Yamada and Yoshitaka Ishisaki (Tokyo Metropolitan Univ.), Andy Szymkowiak (Yale), and Maurice Leutenegger, Kevin Boyce, Scott Porter, Megan Eckart, and Tomomi Watanabe (GSFC). Credit: David Friedlander



Thomas Hams recovers the Tiger mascot—wearing a cape to become a SuperTIGER—while excavating the Super-TIGER cosmic ray experiment in Antarctica in December 2014. The mascot flew on the outside of the payload for 55 days and then spent two years on the ice. “To our delight,” said Hams, “we found him intact.” Credit: Dave White



In 2014, ASD hosted the first Astrophysics/Howard University Interaction Day on April 25. Twelve faculty members from science, engineering and computer science departments and seven physics undergraduate students visited Goddard for the day-long event. Activities included presentations about astrophysics missions in operation and development (Fermi, BETTII, NICER) as well as tours of the Astrochemistry Laboratory in Building 34 and hardware for the James Webb Space Telescope in the Building 29 clean room. A networking pizza lunch gave students and faculty an additional opportunity to meet informally with postdoctoral fellows and additional scientists and engineers. The goal of the interaction day was to foster collaboration between ASD scientists and Howard University faculty, as well as to expose students to our internship opportunities and encourage them to apply. A second interaction day was held at Howard University on Nov. 14. The Howard University Interaction Days were organized by ASD's Padi Boyd, Aki Roberge (front row, left center) and Marcus Alfred at Howard University (back row, far right). Credit: Jay Friedlander



NPP Fellow Brian Williams takes a seat in the cockpit of SOFIA. He had the opportunity to fly on SOFIA to carry out observations of supernovae. Credit: Brian Williams

Intently watching telemetry from the Xcalibur suborbital balloon flight in October 2014 are (from left) ASD's Thomas Hams and Scott Barthelmy, Henric Krawczynski (PI, Washington University, St. Louis), and James Monahan and Takashi Okajima, also from ASD. Credit: Tom Malkowicz



The Xcalibur payload, a hard X-ray polarization experiment, performs a pointing test from the hangar door at Fort Sumner, New Mexico, in September 2014. Credit: Tom Malkowicz





At the Science Jamboree, Fermi scientist Dave Thompson describes to Paul Hertz, NASA HQ, how the micrometeoroid shield for the Fermi Large Area Telescope stops small high-velocity particles. This low-density shield is capable of stopping particles with the equivalent kinetic energy of a Major League fastball. Credit: Elizabeth Ferrara

PROJECTS IN OPERATION

Fermi

The Fermi Gamma-ray Space Telescope continued smooth operation into the sixth year of the mission, showing no degradation in science performance. The past year included a number of scientific highlights. Fermi established classical novae as a class of gamma-ray emitter, provided a deeper look at the enigmatic Fermi Bubbles, and revealed QPOs in magnetar flares. Fermi made the first gamma-ray measurements of a gravitational lens and also uncovered a brand-new phenomenon in a millisecond pulsar binary system that rapidly converted from a radio pulsar into a bright unpulsed gamma-ray emitter. Dark matter and pulsars vied as candidate explanations for the excess of gamma rays observed from the galactic center region. The observatory completed a year-long survey strategically targeting that region while maintaining all-sky coverage. Fermi left that survey for a few weeks to cover the periastron passage of PSR B1259-63 and its accompanying gamma-ray brightening. The project team gathered input from the instrument teams and Fermi Users Group and submitted a proposal for continued Fermi operation to NASA's 2014 Senior Review of Operating Missions. Fermi received a strong endorsement for extension and will continue to provide "unparalleled capability for exploration of high-energy astrophysical phenomena."

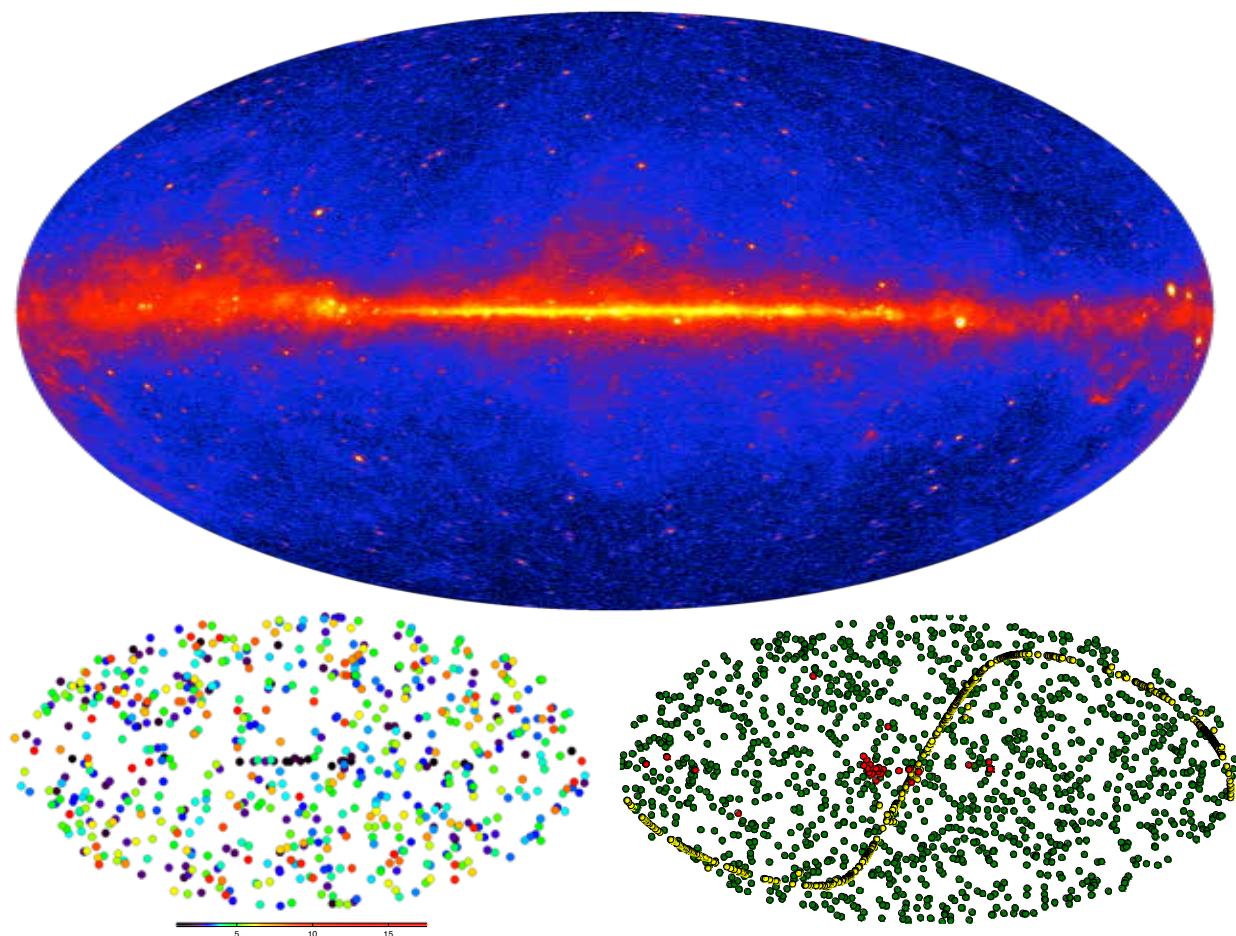
David Thompson and Elizabeth Ferrara contributed to a major team effort to prepare and publish the third catalog of sources from Fermi's Large Area Telescope (LAT), containing more than 3,000 objects. The majority of those sources are active galactic nuclei studied in the LAT data and in multiwavelength context spanning radio to very-high-energy gamma-ray observations. Roopesh Ojha, Michael Dutka, and Bryce Carpenter coauthored a paper exploring the possible connection between gamma-ray-bright AGN and the astrophysical neutrinos discovered by IceCube (Krauss, F., et al. 2014, A&A). Jeremy Perkins, a coordinator for the LAT AGN Science Working Group, led work on detecting very-high-energy emission and modeling the broadband SED for 1ES 0229+200 (Aliu, E., et al. 2014, ApJ, 782, 13). Josefa Becerra Gonzalez fitted gamma-ray data for spectral curvature to constrain the redshift of PG 1553+113 (Aleksic et al. 2014). Bill McConville, advised by Julie McEnery, successfully defended his doctoral thesis, "Investigating the

Origin of Gamma-ray Emission in Non-blazar AGN with the Fermi Large Area Telescope." Jeff Magill joined the group and began work on gamma-ray emission from radio galaxies. Tonia Venters considered possible observational consequences of the intergalactic magnetic field on the signals of gamma-ray emitting galaxies and their contribution to the extragalactic background light. Many group members also served as LAT flare advocates, watching for new sources or brightening of gamma-ray emission and communicating these to the astrophysical community.

Jack Hewitt, Terri Brandt, and Jamie Cohen studied the emerging population of gamma-ray-emitting supernova remnants seen by Fermi LAT. Jack contributed to a paper on gamma-ray emission in the vicinity of W28 (Hanabata, Y., et al. 2014, ApJ, 786, 145) and has been serving as a coordinator for the LAT Galactic Science Working Group. Nestor Mirabel coauthored a paper that used LAT observations to constrain a hypothesized dark matter core for the Smith Cloud, a high-velocity cloud that passed very close to the galactic center this year (Nichols, M., Mirabal, N., et al. 2014, MNRAS, 442, 2883). Jack Hewitt participated in a study searching for dark matter annihilation in this object (Drlica-Wagner, A., et al. 2014, ApJ, 790, 24).

Alex Moiseev, David Green, Liz Hays, and Thompson continued support of the LAT Anticoincidence Detector. David Green conducted a study of adapting the Pass 8 LAT electron analysis and extending that framework to select and characterize the substantial LAT proton data sample for spectral and spatial analysis.

Fermi group members served as burst advocates and pursued a variety of projects to detect and model the prompt and afterglow emission and evaluate burst populations. Sylvia Zhu led the LAT paper on the bright and relatively nearby GRB 130427A (Ackermann, M., et al. 2014, *Science*, 343, 42) with coauthors McEnery, Judy Racusin, Dan Kocevski and other LAT team members. She also contributed to work that established constraints on very-high-energy emission from that burst using VERITAS observations (Aliu, E., et al. 2014, ApJ, 795, 3). Sylvain Guiriec continued exploring enhanced models for GRB prompt emission using additional blackbody components and power laws extending to high energy. In addition to studies of gamma-ray bursts, Kocevski has further developed the LAT real-time search for longer transients on ~1 week timescales.



Fermi studies high-energy phenomena in depth and over time, as illustrated in these all-sky maps in galactic coordinates. Top: Integrated LAT data (>1 GeV) for the first 5 years of the mission. Bottom left: The 655 significantly variable sources in the preliminary LAT 3FGL catalog, color coded by how many times brighter than average they became on monthly time scales. Bottom right: The locations of all 2085 GBM triggers — green for GRBs, yellow for solar flares, and red for soft gamma-ray repeaters, with typical time scales of seconds to minutes.

The Hubble Space Telescope (HST)

Even five years after its final servicing mission, the Hubble Space Telescope continued to achieve top science return in 2014. This year the HST Project focused on NASA’s Senior Review of Operating Missions, where a panel of external experts evaluated extensively HST’s continuing technical health, efficiency, and science return. The panel gave the Hubble Space Telescope mission its highest commendation, concluding that “Hubble is operating at or near the highest level of performance and scientific productivity in its history” and recommending its continued long-term operation. The mission was judged as excellent in every category described (science return, productivity, innovation, community demand, spacecraft and instrument health, cost ef-

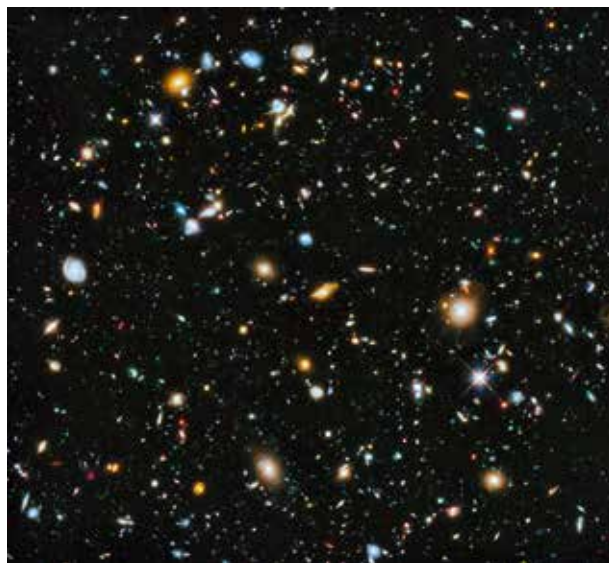
iciency, and science support). “Hubble 2020” has thus become the mission goal, with full operations through 2020 and hopefully years beyond.

Hubble revealed new findings from the distant universe as well as the solar neighborhood. Of particular note was the release of the first spectacular “Frontier Field” image of galaxy cluster Abell 2744. By taking advantage of the natural magnification due to gravitational lensing by massive galaxy clusters, the Hubble Frontier Fields program is mapping cluster dark matter and observing previously unseen populations of distant galaxies, reaching galaxies with intrinsic luminosities 10–100 times fainter than those detected in the Hubble Ultra Deep Field (HUDF). A new version of the HUDF itself was also released this year, adding ultraviolet wavelengths and the broadest spectrum of colors ever included,

allowing diverse studies of very distant sources and the stages of galaxy evolution.

Closer to home, Hubble has been used to analyze the atmospheric composition of exoplanets, a capability not originally foreseen for the mission. Water vapor was detected in the environs of several transiting exoplanets. Solar system observations revealed evidence for colliding asteroids and a shrinking Great Red Spot on Jupiter. In collaboration with NASA's New Horizons mission, Hubble was even used to search for potential Kuiper Belt targets for the probe to visit after its monumental encounter with Pluto planned for 2015. Public interest in Hubble science from diverse sectors continued to soar. New 3-D tactile images and a tactile iBook were released, allowing visually impaired persons to enjoy exploring the universe through Hubble discoveries.

The Project Science Office for HST at Goddard continued its science leadership with ASD scientists Jennifer Wiseman as Senior Project Scientist, Kenneth Carpenter as Operations Project Scientist, Patricia (Padi) Boyd as Deputy Operations Project Scientist, and Jeffrey Kruk as Observatory Project Scientist. This year the Hubble Project Science team initiated the first-ever HST History Project to document the 25 years of HST mission operations since launch. ASD astrophysicist Ted Gull was recruited to help launch this effort to recount, by means of professional historians and archivists, the complicated interplay of scientists, astronauts, engineers, man-



This new version of the Hubble Ultra Deep Field was released in 2014. Spanning ultraviolet, visible, and near-infrared wavelengths, this panchromatic view of the deep universe is the most comprehensive ever achieved.

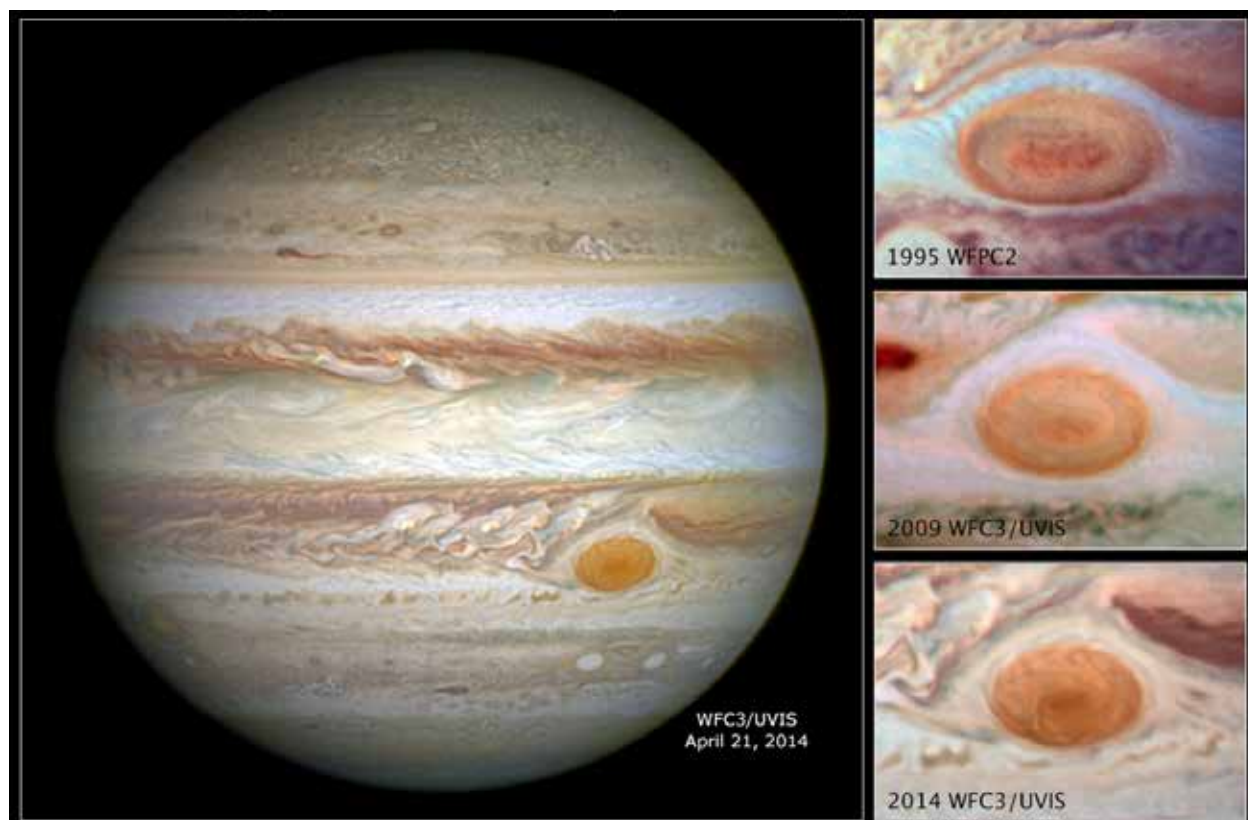
agers, government leaders, and the public throughout the mission.

HEASARC

The HEASARC is NASA's primary archive for astrophysical data from extremely energetic phenomena, from black holes to the Big Bang. Incorporating the

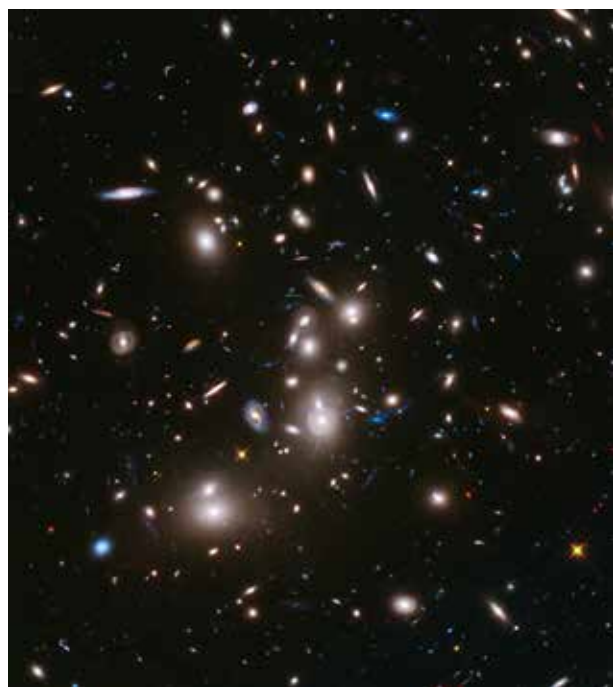


NGC 2174, part of the Monkey Head Nebula, seen in visible (left) and infrared (right) light. The new infrared image was released for Hubble's 24th anniversary and demonstrates the premier capabilities of Hubble's Wide-Field Camera 3, an instrument developed at Goddard and installed on the final HST servicing mission in 2009.



Hubble is monitoring changes in our dynamic solar system. Observations of Jupiter over the past few years show that Jupiter's Great Red Spot is actually shrinking.

Legacy Archive for Microwave Background Data Analysis (LAMBDA), HEASARC curates and maintains datasets obtained by missions that study the relic cosmic microwave background (CMB) as well



as NASA's high-energy astronomy missions from the extreme ultraviolet through gamma-ray bands. The HEASARC archive contained about 70 terabytes (TB) of data at the end of 2014, having grown by ~10 TB during the year, and includes data from seven active missions (Chandra, Fermi, INTEGRAL, NuSTAR, Suzaku, Swift, and XMM-Newton) and from more than 30 space-based missions and sub-orbital experiments that are no longer operational. Papers written using HEASARC data comprise ~10 percent of the total astronomical literature and include some of the most highly cited papers in the field. The HEASARC Office is led by Alan Smale.

Launched in June 2012, NuSTAR is a Small Explorer mission with the first focusing high-energy X-ray telescope in orbit. The HEASARC archive contains NuSTAR data converted into standard FITS format and documentation on the data and data analysis software. By the end of 2014 the archive contained 582 publicly available observations,

With Hubble's Frontier Fields program, the gravitational lensing effect of massive galaxy clusters like Abell 2744, shown here, become tools to study extremely distant lensed galaxies, as well as the distribution of dark matter in the lensing cluster itself.



Hubble's 3-D Tactile Images enable another approach to appreciating Hubble's discoveries, particularly for those with visual impairments.

and the community had downloaded a total of 2.0 TB of data since the archive opened in August 2013. HEASARC data access tools can be used to locate and download data from individual observations, and the NuSTAR data analysis software is distributed to the community as part of the HEASARC's HEASoft data analysis suite. The first AO for NuSTAR's Guest Observer program was released in 2014, with proposals due November 25. Proposers used the HEASARC's ARK/RPS system to submit proposals, and HEASARC tools were available for proposers to simulate observations. Francis Marshall serves as the HEASARC's NuSTAR Archive Scientist, with significant contributions to the NuSTAR archiving effort from Michael Corcoran, Stephen Drake, and Thomas McGlynn.

During 2014, Smale and McGlynn led a successful joint proposal with NASA's other astrophysical archives, MAST and IPAC, to sustain and extend the Virtual Observatory (VO) infrastructure developed under the U.S. Virtual Astronomical Observatory (VAO) program. McGlynn was appointed NASA VO Project Scientist, and tasked with coordinating the astronomical VO efforts across all the archives. McGlynn also served as the VAO Operations Lead until the termination of these activities at the end of September 2014, and managed the transition to the follow-on activities, now rebranded as the NASA Astronomy Virtual Observatories (NAVO).

McGlynn released a complete repackaging of the SkyView virtual telescope that enables it to be easily maintained, updated, and distributed. Over 35 new surveys were added to Skyview in 2014, more than any year since its inception. McGlynn also oversees the continuing development of the HEASARC's Xamin and Browse archive web interfaces, and leads the effort to develop the Hera software system which

provides users with cloud-like analysis capabilities in an environment with access to all HEASARC data.

During 2014, HEASARC programmers under the direction of Smale coordinated a major new release of the HEASoft data analysis software package, providing improved analysis capabilities for data from the NuSTAR, Swift, and Suzaku observatories. The HEASARC staff also enhanced the cloud-based Hera data analysis service which enables researchers to analyze their data over the internet, using HEASoft within the computing environment provided by the HEASARC. The major focus of development has been to integrate Hera more closely with the new Xamin interface, so that researchers can seamlessly query the HEASARC archive to locate relevant observations and then analyze the data using Hera, all within the same Web browser session.

Drake continued to add tables to the HEASARC's archive, bringing the total number of unique tables available at the HEASARC to ~840. Among the newly created tables, 14 were new Chandra source lists, six were new XMM-Newton source lists, and 20 others included source lists from a broad array of missions including BeppoSAX, Fermi, Herschel, INTEGRAL, IRAS, SDSS, Spitzer, and WISE, as well as catalogs of stars, galaxies, and radio sources. Drake serves as the HEASARC's XMM-Newton Archive Scientist, and also maintains and updates the web pages and RSS feeds of the main HEASARC and NuSTAR web sites.

In 2014, Corcoran served as Fermi Archive Scientist for the HEASARC, calibration database manager, NuSTAR associate archive scientist, and editor of the High Energy Astrophysics Picture of the Week, as well as providing general web content and management for the HEASARC website. He consulted with the Fermi Science Support Center and Fermi project on archive, calibration database, and data access issues, and participated in weekly FSSC meetings. Corcoran helped the Fermi project implement full CALDB access in the Fermi Science Tools, implemented the LAT GRB catalog in BROWSE/XAMIN, incorporated the GBM Solar Flare table in BROWSE/XAMIN, and helped define file formats for a new data product, the GBM occultation light curves. In his role as CALDB manager, Corcoran performed over 17 updates of the HEASARC CALDB, including the first release of the NuSTAR CALDB. He devised the method for updates and releases of the NuSTAR CALDB, including the clock correction file, which is updated on a regular basis. Corcoran maintained and updated the Astro-Update website, used by astronomers worldwide to help track updates to important high-energy astronomy analysis

software, and wrote the High Energy Astrophysics Picture of the Week (HEAPOW) as part of his outreach activities. Corcoran also administers the HEAPOW Facebook group, which currently has over 370 members and is increasing at a rate of nearly 1 new member per day.

Keith Arnaud continued his work on the XSPEC spectral fitting tool and related software. Major improvements to XSPEC in the past year included upgrading the models for non-equilibrium ionization collisional plasmas, with much improved physical data provided by the AtomDB project; adding support for Chandra Source Catalog spectra; and overhauling the model calculation code to allow more than one mixing model at a time. Arnaud also rewrote the WebSpec tool to run on top of Hera. In addition, Arnaud continued as Treasurer of the High Energy Astrophysics Division of the American Astronomical Society, monitoring the Division's finances and helping to organize the Chicago HEAD Meeting.

Steven Sturmer is responsible for maintaining the INTEGRAL public data archive at the HEASARC. This activity entails downloading the twice-monthly public data releases from the ISDC in Geneva, installing the data within the HEASARC archive, and overseeing the transfer of weekly metadata updates to the HEASARC. Additional INTEGRAL data are public as soon as they enter the ISDC archive from the processing pipeline; Sturmer monitors the ISDC archive and downloads and ingests such data as soon as they are made available. During the course of the year, Sturmer was responsible for revising and adapting the update process as changes to the computer systems at ISDC changed and evolved, and also for updating the INTEGRAL Guest Observer Facility web pages where needed.

Under the leadership of CMB Archive Scientist David Chuss, the LAMBDA archive continued to grow in 2014, ingesting new data from ground-based cosmic microwave polarization experiments such as BICEP1, BICEP2, POLARBEAR, the Atacama Cosmology Telescope (ACT), and the South Pole Telescope (SPT). New low-frequency survey data have also been added to the archive. In addition, LAMBDA supported an Explorer proposal for the Dark Energy Radio Explorer (DARE), as the designated archive for the mission. On the programmatic side, LAMBDA now resides on common hardware with the rest of the HEASARC, having migrated into the AstroVDC environment. This completes the integration of LAMBDA into the HEASARC, fully combining the two archives in support of NASA's "Physics of the Cosmos" theme.



The JWST flight Integrated Science Instrument Module was fully assembled with all four instruments and underwent a cryogenic vacuum test in 2014. Credit: NASA/Chris Gunn

PROJECTS IN DEVELOPMENT

James Webb Space Telescope (JWST)

The James Webb Space Telescope is a large (6.5m), cold (50K), facility-class general-purpose observatory that will be launched into orbit around the Sun-Earth L2 point. It is the successor to the Hubble and Spitzer space telescopes. Its science goals include detecting the first galaxies to form in the early universe, galaxy evolution, star and planet formation, exoplanets and objects in our solar system. Time on the telescope will be allocated to the community through annual peer-reviewed proposals in a manner similar to Hubble. The prime contractor is Northrop Grumman; the Science and Operations Center is located at the Space Telescope Science Institute. JWST is a partnership between NASA and the European and Canadian space agencies.

ASD provides scientific leadership for JWST through a team consisting of 13 project scientists. The Senior Project Scientist is John Mather, his deputy is Jonathan Gardner and his technical deputy is Malcolm Niedner. The other members of the team are: Matthew Greenhouse (Instrumentation), Bernard Rauscher (deputy); Mark Clampin (Observatory), Charles Bowers and Michael McElwain (deputies); Randy Kimble (Integration and Test); George Sonneborn (Operations), Jane Rigby (deputy), Amber Straughn (Communications) and Stefanie Milam from the Solar System Exploration Division. ASD science staff members



The JWST flight backplane center section and side wings were assembled in 2014 and will be delivered to Goddard in 2015. Credit: Northrop Grumman

are also directly involved in the provision of key flight systems for the JWST near-infrared multi-object spectrograph (NIRSpec), including its detector and microshutter array systems.

Mather chairs the JWST Science Working Group (SWG), and the project scientists work closely with the management and engineering teams, participating in reviews, project meetings, serving on change-configuration boards, and participating in decisions, participating in testing, and reviewing test data. In 2006, the JWST SWG published a thorough description of the JWST science goals and technical implementation as a special issue of the refereed journal *Space Science Reviews*. It has since also updated and extended the science case in a series of white papers that include astrobiology, dark energy, exoplanet coronagraphy, exoplanet transits, first-light galaxies, resolved stellar population, and solar system observations. The *Space Science Reviews* paper and the white papers are available from jwst.gsfc.nasa.gov/scientists.html. There were conferences for community discussion of JWST science in 2007 and 2011, and the next conference is scheduled for October 2015.

The JWST project is currently in development, and is conducting the integration and test phase for many systems. The budget and schedule went through a replan in 2011 and the mission continues to be fully funded for launch in 2018, with no change to the budget or schedule since the replan.

The Integrated Science Instrument Module (ISIM) consists of the four science instruments and nine subsystems. ISIM began its integration and testing phase in 2011. In 2014, all four instruments, the Near-Infrared Camera, the Near-Infrared Spectrograph, the Mid-Infrared Instrument and the Fine Guidance Sensor/Near-Infrared Imager and Slitless Spectrograph were integrated into the ISIM structure, and went through a full cryo-vacuum test. The ISIM and its four instruments will undergo a final cryo-vacuum test in 2015, before being integrated with the telescope in 2016.

The ASD is directly responsible for two flight systems, both within the Near-Infrared Spectrograph (NIRSpec), an instrument that is part of the ESA contribution to the mission. The Microshutter Assembly (MSA) is led by PI Harvey Moseley with contributions from a number of contractor scientists. The MSA will enable simultaneous spectra of more than 100 objects—the first time that a true multi-object spectrograph has flown in space. The MSA is now fully integrated into the instrument. The NIRSpec detector system is also being built at Goddard, under the leadership of PI Bernard Rauscher. Moseley and Rauscher are members of the NIRSpec Science Team and will participate in their Guaranteed Time Observations.

All of the flight telescope optics, including the primary mirror segments, the secondary and tertiary mirrors, and the fine steering mirror, have been completed. Construction of the flight backplane and side wings was completed in 2014 and they will be delivered to Goddard in 2015. The flight mirrors will be installed onto the backplane in the Goddard clean room after that delivery.

When the telescope is complete and the ISIM is finished with its integration and testing, the two will be put together and ambient tested (including vibration and acoustics) at Goddard and then cryo-vacuum tested in the Johnson Space Center Chamber A. The JWST project has modified the historic Chamber A for use in JWST testing by installing a gaseous helium shroud. During 2014, a clean room outside the chamber was completed and the Chamber itself was prepared for a series of cryo-vacuum tests. Initial tests will check out the ground support equipment in preparation for the final test of the flight ISIM and telescope.

Development of the JWST Science and Operations Center at Space Telescope Science Institute is progressing with the rest of the project. Analysis of the Science Operations Design Reference Mission allowed a first look at scheduling and efficiency. Additional science tools include an exposure time

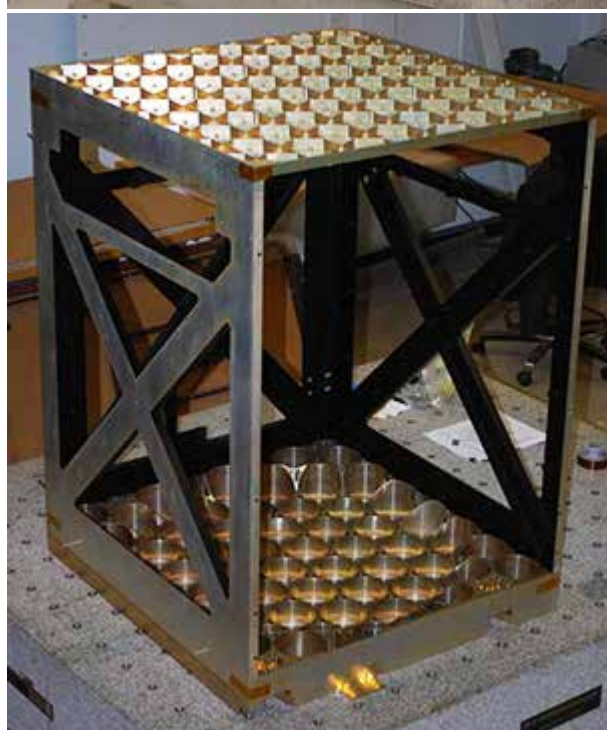
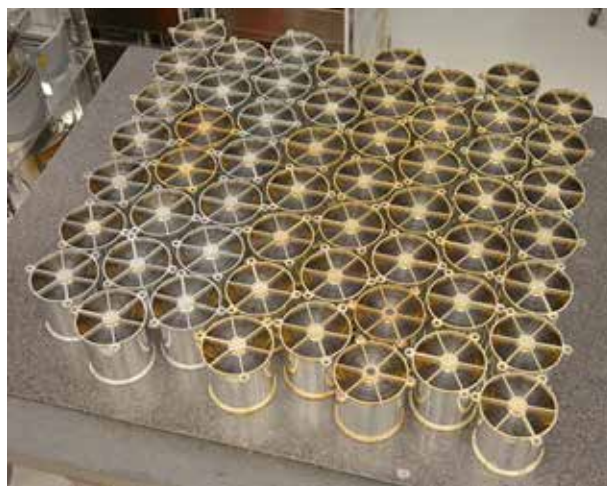
calculator, a point spread function simulator and the JWST astronomer's proposal tool. The first of two comprehensive design reviews of the Science and Operations Center was held in 2014. Data analysis tools to handle advanced coordinate systems, unit conversion, and data modeling, were released as Astropy 1.0.

Outreach to the scientific community in 2014 included town halls at the American Astronomical Society winter meeting and a JWST Workshop on Potential Science Investigations in the Solar System at the Division of Planetary Science (DPS) meeting. The Planetary Science team made a series of flyers for the DPS and has written a series of white papers currently under consideration for publication.

Neutron Star Interior Composition Explorer (NICER)

An Explorer Mission of Opportunity (PI, Keith Gendreau), NICER is an International Space Station (ISS) payload devoted to the study of neutron stars through soft X-ray timing. Neutron stars are unique environments in which all four fundamental forces of nature are simultaneously important. They squeeze more than 1.4 solar masses into a city-size volume, giving rise to the highest stable densities known anywhere. The nature of matter under these conditions is a decades-old unsolved problem, one most directly addressed with measurements of the masses and, especially, radii of neutron stars to high precision (i.e., better than 10 percent uncertainty). With few such constraints forthcoming from observations, theory has advanced a host of models to describe the physics governing neutron star interiors.

By answering a long-standing astrophysics question—How big is a neutron star?—NICER will confront nuclear physics theory with unique measurements, exploring the exotic states of matter within neutron stars through rotation-resolved X-ray spectroscopy. The capabilities that NICER brings to this investigation are unique: simultaneous fast timing and spectroscopy, with low background and high throughput. NICER will also provide continuity in X-ray-timing astrophysics more broadly, post-Ross X-ray Timing Explorer, through a proposed Guest Observer program. Finally, in addition to its science goals, NICER will enable the first space demonstration of pulsar-based navigation of spacecraft, through the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) enhancement to the mission, funded by the Space Technology Mission Directorate's Game-Changing Development program.



Among NICER's completed flight hardware are 56 X-ray concentrators (top) and the Instrument Optical Bench (bottom).

NICER's X-ray Timing Instrument (XTI) represents an innovative configuration of high-heritage components. The heart of the instrument is an aligned collection of 56 X-ray "concentrator" optics (XRC) and silicon drift detector (SDD) pairs. Each XRC collects X-rays over a large geometric area from a ~ 30 arcmin² region of the sky and focuses them onto a small SDD. The SDD detects individual photons, recording their energies with good (~ 3 percent) spectral resolution and their detection times to an unprecedented 100 nanoseconds RMS relative to Universal Time. Together, this

assemblage provides a high signal-to-noise-ratio photon-counting capability within the 0.2–12 keV X-ray band, perfectly matched to the typical spectra of neutron stars as well as a broad collection of other astrophysical sources.

From NICER's ISS platform, a star-tracker-based pointing system allows the XTI to point to and track celestial targets over nearly a full hemisphere. The pointing system design accommodates the ISS vibration and contamination environments, and enables (together with NICER's GPS-based absolute timing) high-precision pulsar light-curve measurements through ultra-deep exposures spanning the 18-month mission lifetime. Anticipated launch of NICER is in late 2016, and additional information is available via the HEASARC (<http://heasarc.gsfc.nasa.gov/docs/nicer>).

NICER was first proposed in February 2011 and selected into Phase A in September 2011. A Concept Study Report was submitted to the NASA Explorers program in September 2012. On Jan. 29, 2013, the NICER team hosted the Explorer review panel at Goddard for a site visit. NICER was selected in Phase B on April 5. The NICER development team has been maintaining its schedule developed in Phase A and successfully completed its Critical Design Review in September 2014. A substantial amount of flight hardware, including 56 X-ray concentrators and the Instrument Optical Bench, has been or is nearing completion. NICER is scheduled to launch on the ISS resupply mission SpaceX-12 in October 2016. The mission team includes MIT (detectors) and commercial partners providing flight hardware; the Naval Research Laboratory and universities across the U.S., as well as in Japan, Canada and Mexico, are providing additional science expertise.

Wide Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA)

The Astro 2010 report *New Worlds, New Horizons*, selected the Wide-Field Infrared Survey Telescope (WFIRST) as the top priority for large space missions in the coming decade. This mission combines dark energy science with observing programs to obtain a census of exoplanets by means of microlensing and to obtain a wide range of near-infrared surveys. In the past two years NASA has baselined an existing 2.4m telescope for the mission and added a coronagraph instrument for direct imaging of exoplanets. This design of the mission is called Astrophysics Focused Telescope Assets or WFIRST-AFTA. The mission is now in pre-phase A study with

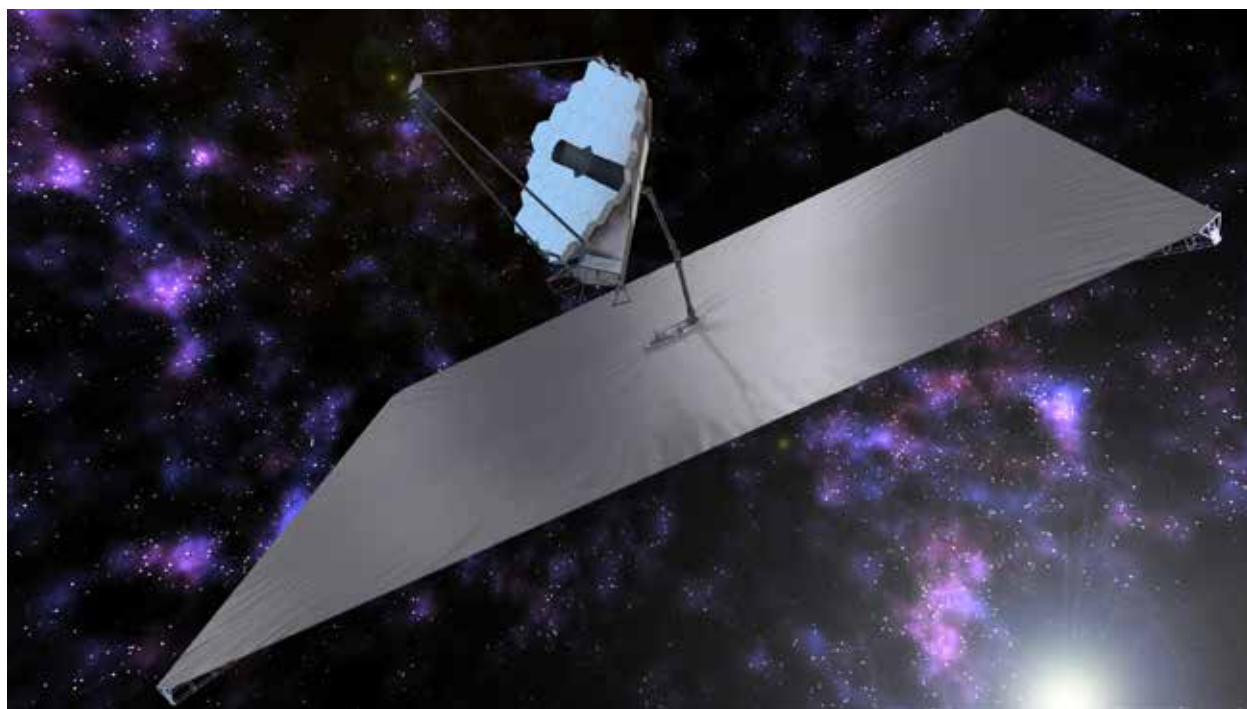
a community Science Definition Team and a Project team at Goddard, the managing institution, and JPL. ASD's Neil Gehrels and Jeff Kruk are, respectively, Project Scientist and Instrument Scientist.

The Science Definition Team was appointed by NASA HQ in October 2012 and has Gehrels and David Spergel of Princeton as co-chairs. The SDT recently completed a two-year study of the mission (http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Final_Report_Rev1_130523.pdf).

The mission will survey more than 2000 square degrees of the sky in the southern region covered by LSST for dark energy and astrophysics studies. The survey will be done in four filter bands between 0.76 and 2.0 microns and with grism spectroscopy. The yield will be 400 million galaxies with shape measurement for weak lensing and 20 million galaxies with spectra for baryon acoustic oscillations. A high-ecliptic-latitude field spanning a few tens of square degrees will be monitored every five days for type Ia supernova measurements. A few-square-degrees low-galactic-latitude field in the galactic bulge will be monitored in several extended campaigns for exoplanet microlensing studies. The coronagraph will perform direct imaging and spectroscopy of exoplanets with a contrast of 10^{-9} and inner working angle of 100-200 milli-arcseconds.

There have been several WFIRST sessions and conferences. Recent ones include special sessions at the winter and summer 2014 AAS and a conference in Pasadena in November 2014.

The WFIRST Project science team at Goddard includes Gehrels, Kruk, John Baker, Rich Barry, Ken Carpenter, Brad Cenko, Bill Danchi, Sally Heap, Marc Kuchner, Mike McElwain, Debbie Padgett, Andy Ptak, Bernie Rauscher (SDT member), Aki Roberge, Amber Straughn, Eric Switzer, and Ed Wollack. This team joins the engineers from the Project Office in working with the SDT to study the implementation of WFIRST.



A design for ATLAST, a concept for a next-generation UVOIR space observatory built around a 9.2-meter segmented mirror.

MISSION AND INSTRUMENT CONCEPTS

ISS-Lobster

ISS-Lobster is a wide-field X-ray transient all-sky monitor proposed for deployment on the International Space Station (ISS). The unique Lobster optics focus 0.3–5 keV X-rays and provide simultaneous wide field of view (900 square degrees), good sensitivity (10^{-11} erg/cm²sec in 2000 sec), and good position resolution (1 arcmin). These characteristics predict a detection rate of numerous transient X-ray sources, including several per year of tidal disruption events, high redshift ($z > 5$) GRBs, and, most importantly, X-ray counterparts of gravitational wave events observed by the LIGO network. ISS-Lobster was submitted as a Mission of Opportunity proposal in December 2012. The proposal received very strong reviews but the opportunity was cancelled due to lack of funding. The ISS-Lobster proposal was re-submitted in December 2014.

Future Large-Aperture Space Observatories

The NASA Advisory Council's Astrophysics Subcommittee released its long-range view,

Enduring Quests, Daring Visions, in late 2013, which among other priorities highlights a large-aperture UV/visual/NIR space observatory as a future agency priority in the 2020s. In response, Harley Thronson established a Goddard team that, in partnership with NASA MSFC, JPL, and STScI, is developing designs, identifying key technology investment areas, and assessing priority science goals for the Advanced Technology Large-Aperture Space Telescope (ATLAST). Our current activity is targeting the 2020 Decadal Survey and a selection as the highest-priority major space astronomy mission for the subsequent decade.

Co-led by Mark Clampin, the team's design work at present is concentrating on operation from wavelengths of about 0.1 micrometers longward to 2.5 micrometers with a suite of instruments capable of carrying out a broad range of scientific programs. One very attractive—albeit extremely challenging—science goal is the search for biosignatures in the spectra of Earth-like worlds in the solar neighborhood. For this goal, an aperture of about 10 meters in diameter appears feasible and fits within currently available launch vehicles. The multicenter team is also considering the opportunities offered by a much larger launch vehicle being developed in coordination with the human space flight program.

Human Operations Beyond Low Earth Orbit

NASA's human space flight program, although with continuing significant uncertainty in its goals and priorities, consistently identifies operations in free space beyond low Earth orbit (LEO) as a priority. Whether as a staging site for long-duration voyages beyond the Earth-Moon system, supporting human and telerobotic exploration of the lunar surface, or advancing technologies developed on the International Space Station, continued human operations in free space have been recommended to NASA for decades as a major enabling capability.

Thronson continues to work with a small team of scientists and engineers at Goddard, other NASA centers, and in industry, which has for several years been developing concepts for how equipment and facilities developed for human space flight might be used to achieve other goals. Such work has a long history at Goddard: In the early 1970s, Frank Cepollina and colleagues persisted in advocating that the space shuttle be adapted to service and upgrade satellites in LEO. This was almost two decades before Cepollina's team used the shuttle to rescue NASA's premier astronomical observatory, the Hubble Space Telescope. Vision and perseverance eventually pays off!

Currently, Thronson and colleagues have taken on the ambitious task of assessing a long-duration

human habitation system to operate in free space in the vicinity of the moon. Its primary purpose would be to develop capabilities necessary for safe and comfortable human operations beyond LEO in the early 2020s. A variety of goals are being evaluated for this habitat, including support for lunar surface operations, either with astronauts or with telerobots, and as an exploration system for an asteroid returned to the Earth-Moon system. However, in addition, the capability to repair, assemble and upgrade complex science facilities, including large optical systems, may also be considered.

To support this, Thronson has been co-chairing a series of Affording Mars workshop planning teams, jointly co-sponsored by Explore Mars, Inc. and the American Astronautical Society. The first workshop was held December 2013 at George Washington University and the second at the Keck Institute for Space Studies. Both workshops critically assessed options for initial human missions to Mars that appear much less costly than scenarios that have been previously developed. The workshops' summaries and recommendations are at <http://www.exploremars.org>.

CUBE/SAT/SMALL/SAT SCIENCE STRATEGIC VISION SCIENCE TASK GROUP (STG) PROJECT

In October, Jeffrey Livas (Gravitational Astrophysics Lab) and Larry Kepko (Space Weather Laboratory), together with a team including representatives from all four science divisions, Wallops Flight Facility, and the Applied Engineering and Technology Directorate (AETD), were awarded an FY15 Science Task Group (STG) Project to formulate an initial strategic vision for the successful development, proposal and execution of CubeSat/SmallSat-based science missions for Goddard Space Flight Center. The strategic science vision is intended to provide guidance to Goddard's Technology Development community as to required and desired capabilities. It will also help focus Goddard's science community on identifying areas where the capabilities of a CubeSat or SmallSat platform may enable science that cannot be done with large flagship-class missions, either because of cost, risk, or capabilities.

The STG project is just the latest in what is an ongoing effort to develop a CubeSat/SmallSat capability at Goddard. Mike Johnson, AETD Chief Technologist, has been leading a team of engineers for several years to mature Goddard small platform capabilities, and together with Kepko has developed the Dellinger platform and a follow-on GTOSat through a CubeSat skunkworks in the Heliophysics Division. They are also developing a modular bus

platform that can be customized to cost-effectively accommodate various science payloads. At the center level, there is a SmallSat Advisory Committee. Wallops hosts a CubeSat Mission Planning Laboratory (MPL), as well as mission operations capability and considerable experience and expertise. Development of a science vision will be a cooperative effort between the STG Project and all of the various interested parties at Goddard, including the Lines of Business advisory groups.

ECG: THE EXOPLANET CLIMATOLOGY GROUP

The exciting and rapidly growing field of exoplanet research is a fine example of interdisciplinary science. In this young and fast-growing field, it is relatively easy for scientists from other disciplines to make significant contributions. It is also a field that, in recent years, largely has been driven by observations rather than theory, providing low-hanging fruit for computer modelers.

So the timing was perfect for the formation of the Goddard Exoplanet Climatology Group (ECG), a collaborative effort between roughly 40 scientists from all four divisions in the Science and Exploration Directorate. The effort is coordinated by Co-PIs Tony DelGenio (GISS), Shawn Domagal-Goldman (Planetary Environments Lab), and Jeremy Schnittman (Gravitational Astrophysics Lab), and represents the evolution of a number of smaller

CubeSat/SmallSat Science STG Team members

Name	Expertise
Jeff Livas/663	Astro CubeSats; constellations
Larry Kepko/674	Helio CubeSat/ SmallSat champion
Bob MacDowall/695	Constellations; LunarCube
Bill Farrell/695	TerDLE CubeSat
Doug Rowland/674	FireFly CubeSat
Dong Wu/613	IceCUBE OI, RAVAN Co-I
Joe Hill/660	CUTE CubeSat FireFly
Keith Jahoda/662	XACT CubeSat
Harvey Moseley/665	CCZAR CubeSat
Pamela Clark/695	CubeSats partners

Name	Expertise
Aprille Ericsson/500	CubeSat Technologist
Mike Johnson/500	Cross-Cutting LOB
Ramsey Smith/504	SBIR/STTR
Tom Johnson/800	WFF CubeSat/ SmallSat Manager
Mike Collier/695	CuPID Cubesat
Dominic Benford/665	CUTIE & SCWERM CubeSats
Scott Porter/662	11 Suborbital missions
Alan Cudmore/582	CubeSat processors
Leroy Sparr/592	HARP CubeSat
TBC	SSAG Liason

projects funded under the Science Innovation Fund (SIF) and Science Task Group (STG) programs over the past few years. The initial goal of these programs was simply to get scientists from different divisions to interact and share ideas about their individual research programs, and it has reaped significant scientific benefits.

In 2014 alone, members of the ECG have written five journal articles, delivered eight conference presentations, won three major NASA proposals, and supported numerous undergrad and graduate students. One of the most exciting and promising areas of focus has been the application of the GISS climate model to neoproterozoic Earth (“snowball Earth”) and also pushing in the opposite direction (“runaway greenhouse”) to determine the inner edge of the habitable zone. In the process, the basic assumptions that go into the global circulation model have been tested, and the quality and reliability of modern climate predictions have been improved. In the coming year, the ECG will invest particular effort on incorporating solar flares and coronal activity into the atmospheric models, probing both the properties of the early solar system as well as the most promising nearby candidates for habitable exoplanets.

EDUCATION AND PUBLIC OUTREACH

During 2014, NASA’s Science Mission Directorate continued to reevaluate its role in STEM education, preparing for an eventual competitive process that will fund endeavors in FY2016 and beyond. Despite uncertainties, the ASD E/PO team continued developing and facilitating a number of successful programs.

The ASD E/PO team has extensive projects that align with the Physics of the Cosmos (PCOS) and Cosmic Origins (COR) program offices, and our team supports NASA astrophysics missions, including Astro-H, JWST, and HEASARC. Barbara Mattson coordinates the team with civil servant support from Smale and Kim Weaver.

PCOS/COR E/PO

The PCOS/COR E/PO team responded to funding cuts and a shrinking team by refocusing its attention to just two of its planned initiatives: Space Forensics and NASA Blueshift. By doing this, the team was able to make tremendous progress on those initiatives in its third funded year.

The Space Forensics project, lead by Sara Mitchell and supported by Mattson and Sarah Eyermann, is a cornerstone element of PCOS/COR E/PO. This project presents astronomical mysteries as detective stories, with a suite of resources for formal and informal education venues. In 2014, the team assembled two comprehensive educator guides with student readings, background information for teachers, and classroom activities. These two guides were submitted to the NASA Education Product Review. The first guide, on supernovae, passed the review with only minor changes recommended. The project’s external evaluator developed tools for evaluating pilot implementation. The team also worked with an external development firm to create an on-line interactive game using the same overarching science stories as the educator guides.

NASA Blueshift, led by Mitchell and Maggie Masetti, provides a behind-the-scenes look at Astrophysics at Goddard through social media. In 2014, the team released blogs highlighting mission milestones, scientific discoveries, and Division scientists, interns, grad students and post-docs. Blueshift continued to connect with the public through social media, increasing its Twitter following over the course of the year to 47,000+ followers and more than tripling its Facebook likes to 65,000+.

Astrophysics Missions E/PO

HEASARC

The HEASARC E/PO program continues to fulfill its mission of bringing high-energy astronomy to teachers and their students. Mattson leads the E/PO program with team members George Gliba, Meredith Gibb, and J.D. Myers. The Imagine the Universe! website provides the foundation for HEASARC E/PO, with information for the general public and resources for the classroom. Mattson and Gibb completed a site-wide update to modernize the look of the site and to bring the information on the site up-to-date with current research. During 2014, Gliba filled over 950 requests for our educational materials from educators across the country—an increase of more than 200 fulfilled requests over 2013.

JWST

JWST E/PO and Communications is a partnership between Goddard, the Space Telescope Science Institute, and other contractor collaborations. This has been an active year for JWST. NASA Administrator Bolden and Senator Mikulski visited JWST to view progress and congratulate the team for the delivery of all the flight instruments. JWST par-



Dr. Neil deGrasse Tyson (right) visited with Goddard Space Flight Center Director Chris Scolese (center) and members of the James Webb Space Telescope team. Credit: NASA's Goddard Space Flight Center/Rebecca Roth

ticipated in South by Southwest, a music, film, and technology festival held in Austin, Texas, again this year. The JWST presence included ongoing demonstrations, speakers, exhibits and interactive activities. Neil deGrasse Tyson visited Goddard, meeting with Center Director Chris Scolese and speaking with the James Webb Space Telescope team. Tyson toured the testing facilities and received a JWST presentation.

JWST continued its strong social media presence, with efforts led by Masetti. Social media has grown a great deal over the past year, with the Twitter feed growing by more than half to 157,000 followers and the Facebook page up by two-thirds to 260,000. The YouTube channel grew by over a third to 9,000 subscribers and the Instagram account increased by half to 7,500.

Suzaku & Astro-H

This year, Astro-H E/PO, led by Mattson, continued the legacy of Suzaku E/PO. The Collaboration Across Cultures website provides continuity for audiences from one mission to the next.

Grants and External Collaborations

In 2013, the Afterschool Universe (AU) and Family Science Night (FSN) teams, led by Eyermann and Mitchell, respectively, applied for an HST supplemental grant (science PI, Jane Rigby) to create and evaluate new sessions for these programs related to Rigby's research on galaxies. AU and FSN are both thoroughly evaluated curricula that have been part of the ASD E/PO portfolio since 2006. During 2014, the teams worked with Rigby to identify significant educational themes in the study of galaxies, and began to develop new content for AU and FSN. In addition, they worked with an external evaluator to develop instruments that can be utilized in the pilot testing of these additions.

The ASD EPO team participated for a third year in the NASA-wide collaboration "NASA Science4Girls and Their Families," which offers informal science events in public libraries nationwide in celebration of Women's History Month. The team provided resources to the Cerritos Library in Cerritos, Calif., to run an event for 8–12 year-olds in May. In addition,

the ASD EPO team provided a scientist to support a local event in Howard County in March.

ASD Press and Communications

Press releases and web features are the primary means of communicating ASD science news to the general public. The ASD Press Officer, Francis Reddy, fills this crucial role for the Division, and he produced 26 releases and features over 2014 on Fermi, Swift, and other Division-related news. Two-thirds of these products were accompanied by videos, which represents a substantial increase

over previous years. Eight stories were repurposed for distribution on Goddard's NASA Visualization Explorer, an app for iOS devices. This activity doubled the number of astrophysics entries on the NASA Viz platform, resulting in combined totals exceeding 3 million views in 2014.

Finally, the ASD E/PO Group Facebook page, NASA Universe Education, led by Mattson, increased its following over the year by more than a factor of ten to 850,000+ likes. This page features the High Energy Picture of the Week and links to the Division's press releases and web features.

NEW FACES

Daniel Angerhausen



In October, Daniel joined the ASD as a NASA Postdoctoral Program (NPP) Fellow under the supervision of Mark Clampin. His main research field is spectrophotometric observations of exoplanet occultations and phase curves using different optical and infrared instruments on various ground-, space- and airborne platforms. A highlight of his career so far was making the first exoplanet transit observations while flying on the Stratospheric Observatory for Infrared Astronomy (SOFIA), the world's largest airborne observatory. Daniel came to Goddard to learn how to apply his expertise in this field to future missions such as TESS and JWST. He was previously a postdoctoral fellow at Rensselaer Polytechnic Institute and at the Hamburg Observatory. He completed his Ph.D. as the first graduate of the German SOFIA Institute in Stuttgart and spent part of his doctoral studies at NASA JPL as a German Academic Exchange Service Fellow.

Heather Audley



Heather joined ASD in July as an NPP Fellow, having earned her doctorate at the Max Planck Institute for Gravitational Physics in Hannover, Germany. During her doctoral studies, she was a member of the LISA Pathfinder mission collaboration and was primarily involved in preparations for the in-flight characterization of the optical metrology system. In a slight change of topic, she has joined the X-ray Calorimeter Group, where she works on the development of transition-edge sensor (TES) microcalorimeters. Specifically, she is interested in Hydra TES microcalorimeters, which use a single transition-edge sensor coupled to multiple absorber elements and may have applications in future X-ray satellite observatories.

Joleen Carlberg



Joleen began as an NPP in September. She received her Ph.D. from the University of Virginia in 2011 and spent the next three years as the Vera Rubin Postdoctoral Fellow at the Carnegie Institution of Washington's Department of Terrestrial Magnetism. Her research interests are in red giants and the fate of exoplanets around these aging stars. She has used optical and infrared spectra to look for signatures of planet engulfment in red giants, such as enhanced stellar rotation and the replenishment of elements destroyed during stellar evolution (lithium, beryllium, and boron). Joleen will be working with Ken Carpenter to use ultraviolet spectra to measure boron and beryllium abundances and study the stellar winds of red giants, focusing on those known to be fast rotators or enriched in lithium.

Will Fischer



Will is an NPP Fellow who joined ASD in July. He works with Deborah Padgett to find young stellar objects in images obtained by the Wide-Field Infrared Survey Explorer and perform follow-up observations. As an all-sky survey, WISE can uncover examples of star formation outside the famous regions explored by previous space missions. More generally, Will specializes in interpreting infrared imaging and spectroscopy of protoplanetary disks and envelopes, including characterizing their variability. He is also interested in rare but important luminosity outbursts in deeply embedded protostars. Will earned his Ph.D. from the University of Massachusetts in 2008, working with co-advisors Suzan Edwards and John Kwan, and did his first postdoc with Tom Megeath at the University of Toledo, in support of the Herschel Orion Protostar Survey. In the spring of 2014, Will was a visiting professor at Oberlin College. Will lives in Bowie with his wife Meredith and daughter Anna.

Rubab Khan

Rubab joined the ASD as a JWST Fellow in the fall. At Goddard, he is pursuing JWST pathfinder science in collaboration with George Sonneborn at the Observational Cosmology Lab. His research focuses on the effects of episodic mass loss in the last stages of stellar evolution on the fate of the stars, circumstellar dust formation and the chemical enrichment of galaxies. Primarily using archival data from the Hubble, Spitzer and Herschel space telescopes, Rubab plans to better understand the relation between star formation and stellar feedback and identify the most promising targets for JWST spectroscopy in galaxies at 1–10 Mpc while producing deep mid-IR point source catalogs as a resource for planning JWST observing missions. He received his Ph.D. in Astronomy from Ohio State University for an observational study of the most massive extragalactic stars under advisors Kris Stanek and Chris Kochanek, and his A.B. in Astrophysics from Columbia University while developing empirical searches for gravitational wave transients under advisor Szabi Marka.

Simin Mahmoodifar

Simin joined ASD's X-ray Astrophysics Lab in November after finishing a two-year postdoctoral position at the UMD Physics department. She is now working under the supervision of Tod Strohmayer. Her research interests are in exploring the interior composition of neutron stars using X-ray observations and in particular neutron star seismology. She is currently carrying out a comprehensive search for global oscillation modes in accreting millisecond X-ray pulsars using data from NASA's Rossi X-ray Timing Explorer. She is also doing simulations of X-ray burst oscillations in neutron stars, as well as theoretical modeling of the light curves produced by different oscillation modes in order to interpret any observed X-ray modulations in terms of the amplitudes of surface motions associated with these modes. Simin received her Ph.D. in May 2012 from Washington University in

St. Louis, where her dissertation focused on probing the phases of cold ultra-dense matter using neutron star physics.

Nestor Mirabal

Nestor joined ASD as an NPP Senior Fellow in September to work with the Fermi team. At Goddard, he hopes to implement machine-learning techniques to solve the mystery of unasociated sources that constitute roughly a third of the Fermi catalog. He is also studying the region around the galactic center in gamma rays. He was previously a Ramon y Cajal Fellow/Assistant Professor at Universidad Complutense de Madrid working on Fermi-related science and dark matter searches as part of the Cherenkov Telescope Array collaboration. He received his Ph.D. from Columbia University. Working at NASA has been a lifelong dream and he hopes to make the most of this wonderful opportunity.

Marc Rafelski

Marc joined ASD as an NPP Fellow in July. His primary research while at Goddard is to measure the evolution of the star formation efficiency of hydrogen-rich galaxies to differentiate possible scenarios responsible for the observed reduced efficiency. Before joining Goddard, Marc was a postdoc at the California Institute of Technology working with Harry Teplitz on ultraviolet imaging and near-infrared grism observations of intermediate redshift galaxies and investigated the sudden decrease in metal content in neutral hydrogen gas at high redshift. He completed his Ph.D. at UC San Diego with Arthur Wolfe, where he studied neutral atomic hydrogen gas associated with high-redshift galaxies via quasar absorption line systems. In particular, his research focused on star formation properties and the evolution of the metal content of the gas. He is interested in many aspects of galaxy formation and evolution, including the metal enrichment of galaxies and the intergalactic medium. He is excited to be at Goddard

and looks forward to interacting with and learning from the astrophysics community.

Christopher Russell



Chris joined ASD's X-ray Astrophysics Laboratory in November as an NPP Fellow working with Tim Kallman. His main project is to develop hydrodynamic and radiative transfer models of gamma-ray binaries, which are massive-star-plus-compact-object binaries that emit all the way into the TeV regime.

He is also interested in synthesizing the X-ray emission that originates from the collision of supersonic stellar winds in massive binaries such as Eta Carinae and in higher-order systems like the galactic center, where the collision of winds from dozens of massive stars orbiting the supermassive black hole generate spatially resolved X-rays. He previously had a one-year postdoc appointment in Sapporo, Japan, at Hokkai-Gakuen University, followed by seven months at the University of Delaware, which is where he earned his Ph.D. in 2013. During graduate school, Chris had a GSRP appointment through Goddard, and he is excited to continue the fruitful collaborations developed during this time.

Leo Singer

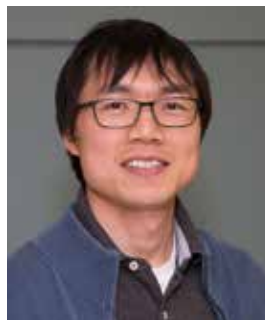


Leo joined ASD as an NPP Fellow and is working on Swift under Neil Gehrels. He looks forward to an exciting year as Advanced LIGO begins collecting science data and as multimes-senger observations with LIGO, Swift, Fermi, and the Palomar Transient Factory (PTF) start to take off. He

earned his Bachelor's degree in 2009 at the University of Maryland and his Ph.D. in physics from the California Institute of Technology in 2014. His thesis work, supervised by Profs. Alan Weinstein and Shri Kulkarni, was on using wide-field optical transient survey instruments to search for electromagnetic counterparts of gravitational wave sources. By day, he worked on real-time detection and sky localization of binary neutron star mergers for LIGO. By night, he tracked down optical afterglows

of gamma-ray bursts detected by the Fermi Gamma-Ray Space Telescope by using the PTF to tile hundreds of square degrees on the sky.

Wonsik Yoon



Woonsik joined the ASD as an NPP fellow in October to work with Caroline Kilbourne in the X-ray microcalorimeter group. He is interested in the development of multi-pixel high-resolution X-ray detectors using magnetic calorimeters and transition-edge sensors, which have various

applications in astrophysics and nuclear physics. He is currently working to develop a microwave SQUID multiplexing readout system for X-ray microcalorimeters in collaboration with Harvey Moseley in the Observational Cosmology Laboratory. He is pleased to be able to interact with and learn from instrument scientists and the astrophysics community at GSFC. Wonsik obtained his Ph.D. at the University of Science and Technology in Korea, where he studied the metallic magnetic calorimeter, one type of cryogenic particle detector. His work included thermal simulation and fabrication of the detectors and its application to alpha and Q spectroscopy.

Awards

In 2014, the numerous contributions of ASD scientists were recognized by NASA, Goddard and by scientific societies.

The success of the James Webb Space Telescope (JWST) Backplane Test garnered the team a NASA Group Achievement Award, which is presented for an outstanding group accomplishment that has contributed substantially to NASA's mission. The team includes ASD's Randy Kimble, who serves as the JWST Integration and Test Project Scientist.

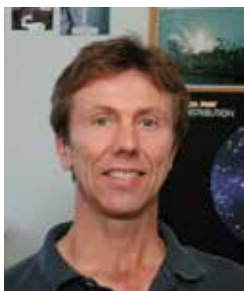
Mark Clampin, the JWST Observatory Project Scientist, was elected as a Fellow of SPIE, the international society for optics and photonics, for his achievements in astronomical optics. He was also named the first editor-in-chief of SPIE's Journal of Astronomical Telescopes, Instruments, and

Systems, a new peer-reviewed journal serving the astronomical instrumentation community.

Elizabeth Hays, Deputy Project Scientist for the Fermi Gamma-ray Space Telescope, was elected as a Fellow of the American Physical Society for her "discovery of high-energy gamma-ray flares from the Crab Nebula in Fermi data and her major contributions to the success of the Fermi project." Fermi Project Scientist Julie McEnery was elected as vice-chair/chair of the American Physical Society's Division of Astrophysics. She begins the four-year appointment as vice-chair and, after two years, becomes the division chair.

Lastly, Sally Heap was presented with a certificate recognizing her 45 years of service to NASA and the U.S. government.

Astroparticle Physics Laboratory



Dr. Neil Gehrels
Lab Chief

Laboratory Overview

The Astroparticle Physics Laboratory (Code 661) conducts research in cosmic ray and gamma ray high-energy astrophysics. Researchers investigate high-energy phenomena in the universe in terms of unified theories of fundamental interactions. The laboratory conducts a broad range of observations from space and balloon instruments of the origin, nature and effects of gamma rays and cosmic rays. The birth and evolution of black holes and other compact objects is a key area of investigation. The laboratory emphasizes the development of new detectors and instrumentation technologies. The laboratory has 15 civil servant scientists and 61 contract and university scientists, engineers, technicians, post docs, and grad students.

Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Lorella Angelini	High-energy astrophysics, data systems	HEASARC Suzaku Swift Astro-H	Project Scientist Deputy Project Scientist Archive Lead Archive Lead Archive/Data Center Lead
Scott Barthelmy	Gamma-ray bursts (GRBs), gamma-ray spectroscopy and polarimetry, instrument development	Swift GCN INFOCUS ISS-Lobster	Lead Scientist (BAT) Project Scientist Principal Investigator Principal Investigator Deputy Principal Investigator
Theresa Brandt	Particle astrophysics, supernova remnants, cosmic rays, instrument development	Fermi Super-TIGER	LAT Team Member
Brad Cenko	GRBs, instrument development, supernovae, tidal disruption flares, time-domain astronomy	Swift Fermi WFIRST-AFTA	Deputy Project Scientist Study Scientist <i>University of Maryland</i> <i>JSI</i>
Tom Cline	GRBs	Swift	Emeritus
Neil Gehrels	Gamma-ray astronomy, time domain astronomy, IR astronomy, instrument development	Swift Fermi WFIRST-AFTA ISS-Lobster	Principal Investigator Deputy Project Scientist LAT Team Member Project Scientist <i>University of Maryland</i> <i>Penn State University</i>
Robert Hartman	Gamma-ray astronomy	Fermi	Emeritus

Scientist	Research Interest	Project/Mission	Role/Affiliation
Elizabeth Hays	High-energy gamma-ray sources, instrument development	Fermi	Deputy Project Scientist LAT Team Member <i>JSI</i>
Stanley Hunter	Galactic diffuse emissions, experimental gamma-ray astrophysics, gamma-ray polarimetry, detector development	3-DTI AdEPT	NASA PI
Julie McEnery	GRBs, high-energy astrophysics, instrumentation	Fermi	Project Scientist LAT Team Member <i>University of Maryland</i>
John Mitchell	Experimental particle and gamma-ray astrophysics, instrument and detector development	BESS-Polar CALET HELIX ISS-CREAM Super-TiGER NASA Scientific Balloon Program	NASA PI Institutional PI Institutional PI Institutional PI Institutional PI Project Scientist
Jeremy Perkins	Active Galactic Nuclei (AGN), high-energy astrophysics, instrumentation	Fermi	LAT Team Member
Judith Racusin	GRBs, supernova remnants, high-energy astrophysics, instrumentation	Fermi Swift ISS-Lobster	Deputy Project Scientist LAT Team Member
Donald Reames	Astrophysics of energetic-particle acceleration at the sun, in the heliosphere and in the galaxy	Wind/EPACT	Emeritus
David Thompson	Multiwavelength astrophysics, particularly of AGN and pulsars, high-energy astrophysics, instrumentation	Fermi	Deputy Project Scientist LAT Team Member
Tonia Venters	Astroparticle physics, diffuse emissions	Fermi	LAT Team member
Tycho von Rosenvinge	Energetic particles in the heliosphere, their acceleration, composition, and transport	ACE, STEREO, Solar Probe+	Project Scientist Co-Investigator Co-Investigator

SCIENCE HIGHLIGHTS

Swift Detection of a Superflare from DG CVn

On April 23, 2014, the Swift Burst Alert Telescope (BAT) detected a hard X-ray transient which turned out to be a “superflare” from one of the low-mass stars in the solar neighborhood. The source was DG CVn, an unresolved visual dM4e + dM4e binary about 59 light-years distant. The BAT trigger resulted in an automatic slew to the source so that the narrow-field Swift instruments, the X-Ray Telescope (XRT) and the Ultraviolet/Optical Telescope (UVOT) could ob-

serve this event, which proved to be exceptional in several ways.

Swift observations of this source continued intermittently for three weeks and provide a rich dataset for this energetic event, which reached a peak X-ray luminosity of 1.9×10^{32} erg/s—exceeding the normal system bolometric luminosity of 1.3×10^{32} erg/s—and a peak temperature of 300 MK, 10 times hotter than the typical solar flare. The first large flare was followed several hours later by a second X-ray flare about one-quarter as strong, and a series of successively weaker flares followed in the next two weeks as the X-ray emission declined to its normal level.

DG CVn has the space motion and other characteristics indicative of membership in the young

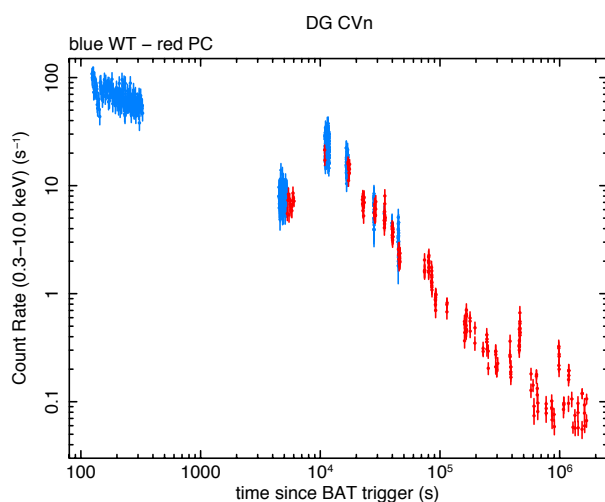


Artist's impression of the DG CVn system and a superflare from one of the stars. Credit: NASA's Goddard Space Flight Center/S. Wiessinger

(<< 1 Gyr) star population which is scattered throughout the solar neighborhood, with a likely age of ~ 30 Myrs. It had previously been detected as an unusually strong stellar radio source and an “ultrafast rotator” with a period less than half a day, and this X-ray flare confirms its extreme levels of activity. Flares of this level would drastically affect the environment of any potential planets in the hab-

itable zone, 0.1 AU away from the star in question, and probably inhibit life from developing if they occurred frequently enough. A similar strength X-ray superflare was detected by Swift in 2008 from the nearby 100-Myr old M dwarf EV Lac, suggesting that low-mass stars can produce such large events until they are at least this old and that this was not a unique event.

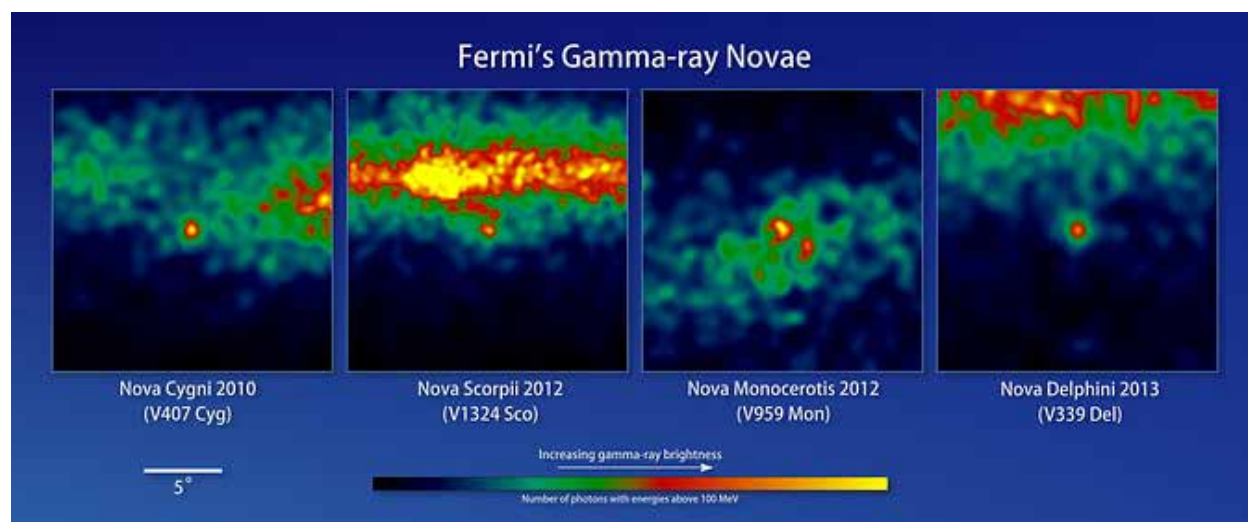
A release and video featuring interviews with ASD's Stephen Drake and Rachel Osten of the Space Telescope Science Institute was issued by Goddard in September. A paper on the event, led by Osten, is in preparation. Drake also led a white paper analyzing stellar flares in the context of the expected number of detections by a newly proposed wide-field X-ray sky monitoring mission, the Large Observatory for X-ray Timing (LOFT).



Swift/XRT soft X-ray lightcurve of the DG CVn superflare peak and decline plus subsequent smaller flares over a 2.5-week time interval. The colors correspond to different instrument modes.

Fermi Reveals Novae to be New Class of Gamma-ray Sources

Novae are bright optical outbursts from binary systems in our own galaxy. In these systems, material from a star accumulates onto a nearby white dwarf companion. When the accumulated mass reaches a critical limit, it ignites a thermonuclear explosion on the surface of the white dwarf, launching material into the surrounding environment. The optical light intensity builds and fades during the following



These images show Fermi gamma-ray data centered on four novae observed by the Large Area Telescope. Colors indicate the number of detected gamma rays with energies greater than 100 million electron volts (blue indicates lowest, yellow highest). Credit: NASA/DOE/Fermi LAT Collaboration

weeks and months. Observations made by the Fermi Large Area Telescope show that novae also routinely produce a signal in gamma rays.

In March 2010, NASA's Fermi Gamma-ray Space Telescope found its first gamma-ray nova, an outburst from V407 Cygni that generated gamma rays within days of the peak in optical brightness. Initial studies suggested that the stellar companion, a red giant, or its accompanying wind could provide radiation fields and circumstellar material to enhance gamma-ray production by charged particles accelerated in the nova blast wave. Because most novae systems do not contain a red giant companion or an accompanying boost in gamma-ray brightness, astronomers concluded that Fermi detections of novae should be the exception and not the rule.

Fermi discoveries of four additional gamma-ray novae in the past three years have changed that picture. Gamma-ray novae are not rare. Common classical novae, with a main sequence, sun-like companion instead of a red giant, emit gamma rays too. The conditions necessary for producing detectable gamma-ray emission are not as rare as implied by V407 Cygni. All bright optical novae make good candidates for a gamma-ray signal.

Gamma rays from novae arise when electrons and protons accelerated in the shock wave interact with radiation fields and matter in the system. The gamma-ray production depends strongly on the maximum energy attained by the accelerated particles and the surrounding distribution of starlight and material. The acceleration is similar to what occurs in blast waves from supernovae, but it happens much more quickly, over days and weeks instead of

hundreds of years, limiting the maximum energy attained by the particles. Additionally, the circumstellar material in classical novae has lower density than in supernova remnants. The Fermi observations demonstrate that the maximum particle energy and the photon and matter densities in classical novae are sufficient to generate detectable gamma rays.

The discovery of several gamma-ray novae elevates these from an anomaly to an established class of gamma-ray sources. Even more interesting, the spectral shape and time evolution show far more homogeneity than the optical features among the set. This probably indicates that the gamma-ray production is less sensitive to some variations in the white dwarf and its surrounding environment than the lower frequency emission. Because the majority of the gamma-ray novae are not special, beyond a tendency to be optically bright and not too distant from Earth, the task now becomes to add more detections, to test the details of the gamma-ray production mechanisms, and to learn what insights these data provide about shock acceleration to high energies happening nearby on accessible time scales.

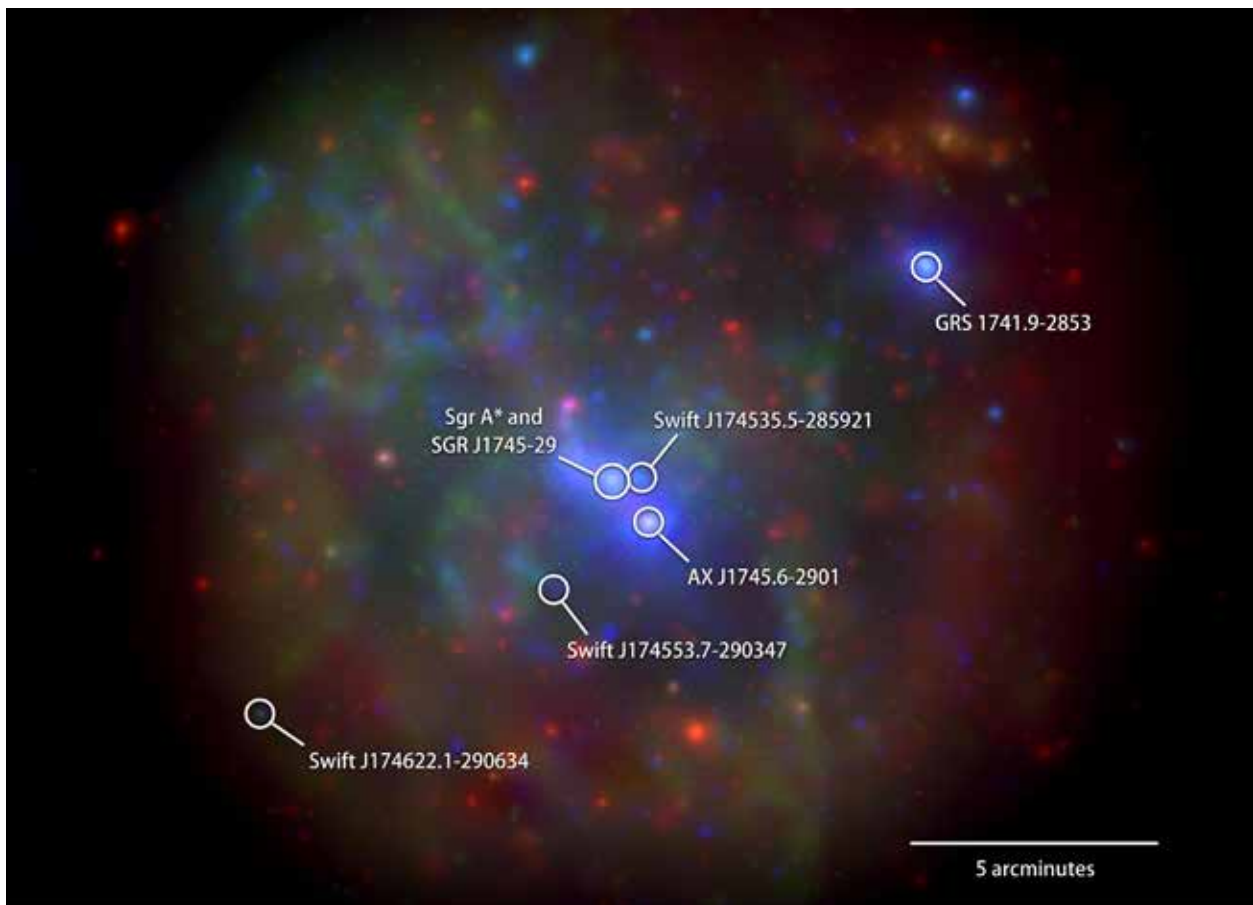
Galactic Center Observations by Swift

Sagittarius A* (Sgr A*) is a ~4 million solar mass black hole that forms the dynamical center of the Milky Way. A key property of our galactic nucleus is that its bolometric luminosity is about nine orders of magnitude lower than expected for Eddington-limited accretion onto a supermassive black hole of that mass. Investigating the fueling process of Sgr

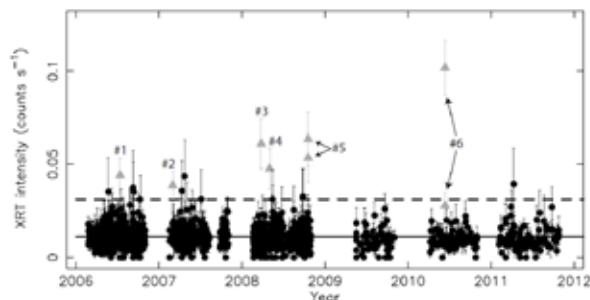
A* may help to understand a large population of dim galactic nuclei and to place these objects into context with brighter supermassive black holes. Recent observations by the Swift mission are revealing many characteristics of this remarkable object.

Despite its relative quiescence, the X-ray emission of Sgr A* occasionally flares up by one to two orders of magnitude for tens of minutes to a few hours. These X-ray flares originate very close to the black hole, within ~ 10 Schwarzschild radii, and are thought to be either related to accretion events (e.g., the infall of gas clumps or the disruption of small bodies, such as asteroids or comets), or magnetic reconnection and electron acceleration processes. The X-ray flares thus allow investigation of the inner accretion flow and offer a new view of the accretion processes at work in our galaxy's nucleus.

Constraining the repetition rate and spectral properties of X-ray flares is an important aspect of understanding the cause and emission mechanism producing these events. Swift has played a key role in this: Starting in 2006, Swift has been taking quasi-daily ~ 1 -ks long XRT images of the center of our galaxy. The excellent baseline provided by Swift's galactic center monitoring campaign allowed the detection of six bright flares (during which the X-ray emission increased by a factor of ~ 100) between 2006 and 2011. This more than doubled the number of such bright X-ray flares observed at the time; previously only four similarly bright events had been detected, two each by Chandra and XMM-Newton. Most importantly, Swift's program allowed for an estimate of the recurrence time of these bright events (about once every week) and revealed that



This X-ray image of the galactic center merges all Swift XRT observations through 2013. Sgr A (center) is labeled, as well as several other important sources. The magnetar SGR J1745-29 is so close to Sgr A* that the XRT cannot separate them. GRS 1741.9 and AX J1745.6 are known to be binary systems where one member is a neutron star. The others, all new Swift discoveries, are binaries containing either a neutron star or a black hole. Low-energy X-rays (300 to 1,500 electron volts) are shown in red, medium-energy (1,500 to 3,000 eV) in green, and high-energy (3,000 to 10,000 eV) in blue. The total effective exposure time is 12.6 days, and the field of view is 25 arcminutes across. Credit: NASA/Swift/N. Degenaar (Univ. of Michigan)*



The X-ray light curve of Sgr A observed by the Swift X-Ray Telescope, after Degenaar et al. (2013). Six flares are evident.*

X-ray flares of similar brightness can have different spectral shapes.

After April 2013, Swift's view of Sgr A* became "obscured" due to the activation of the nearby magnetar SGR J1745-29, separated by only ~ 5 arcseconds and with a 2–10 keV X-ray luminosity about 100 times brighter than that of the supermassive black hole. However, the magnetar displayed a steady fading and Swift's view of Sgr A* cleared again in 2014, illustrated by the detection of another bright flare—the brightest caught by Swift so far—on Sept. 10.

PROJECTS IN OPERATION

Swift

Swift is a NASA Explorer mission, with international participation, that is designed to find gamma-ray bursts and other transients and study them over a wide range of wavelengths, from gamma rays to optical light. It was launched in 2004 and is in its extended mission phase with re-entry no earlier than 2025. There are three telescopes aboard Swift: the Burst Alert Telescope is a coded-aperture hard X-ray detector that operates between 15 and 150 keV; the X-Ray Telescope observes in the 0.2–10 keV energy band; the UltraViolet/Optical Telescope collects data between 1600 and 6000 angstroms.

In ten years since launch, Swift has detected and localized more than 900 GRBs. Some of the mission's most recent key scientific accomplishments have been:

- Discovering the first short hard burst (GRB 130603B) associated with a "kilonova." These observations provided strong support for the theory that short bursts are due to the merging of binary neutron stars.
- Making high-quality metallicity measurements of star-forming regions at the highest redshifts ($z > 5$) using GRBs
- Detection of bright gamma-ray and X-ray flare emission from the active star system DG CVn in April 2014. The flare intensity was 10,000 times that of large flares from our sun.
- Discovering new types of transients, such as ultralong GRBs; relativistic tidal disruption events; supernova shock breakouts; and extreme stellar explosions, such as the record-setting GRB 130427A
- Detection of six X-ray flares from the black hole at the center of our Milky Way galaxy, Sgr A*
- Discovering the first pulsar anti-glitch in magnetar 1E2259+586 in the RCW 103 supernova remnant. These observations call for a rethinking of glitch theory for all neutron stars.
- Discovering SGR J1745-29, a new magnetar located just arcseconds from Sgr A* at the galactic center.

Swift has been widely recognized as a ground-breaking mission. It was ranked first in the 2012 Senior Review. By the end of 2014, nearly 2,500 refereed papers have been published based on Swift results, with 45 discovery papers in either *Nature* or *Science*.

The Swift Guest Investigator Program adds an important peer-reviewed component to the Swift



Artist's rendering of the flaring star in DG CVn, a binary system that unleashed a series of powerful flares detected by NASA's Swift. At its peak, the initial flare was brighter in X-rays than the combined light from both stars at all wavelengths under typical conditions. Credit: NASA/Casey Reed

research and includes both GRB and non-GRB science. During the 2014 Cycle 11, 165 proposals were received, requesting \$5.3M in funds and 14.1 Ms total exposure time for 1,044 targets. The oversubscription rate is a factor of 4.4. Forty additional proposals were received through the Swift Guest Investigator joint programs.

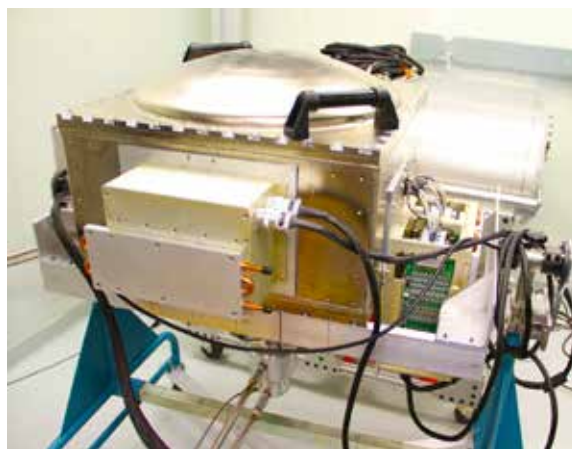
Goddard scientists involved in Swift are Angelini, Barthelmy (PS), Baumgartner, Boyd, Camp, Cannizzo, Cenko (DPS), Cline, Cucchiara, Cummings, Gehrels (PI), Krimm, Lien, Markwardt, Marshall, Racusin, Smale, and Troja.

MISSION AND INSTRUMENT CONCEPTS

RATIR and RIMAS

The Reionization And Transients InfraRed (RATIR) camera has been successfully operating at San Pedro Martir observatory of the Universidad Nacional Autónoma de México (UNAM) in Baja California. The instrument follows up Swift GRB triggers in

an automated mode. Since the beginning of its operation in December 2011, RATIR has followed up 59 events, producing photometry in the visible and infrared bands. The project is a collaboration between Goddard (Gehrels, Kutyrev, Moseley, Troja), UC Berkeley, ASU (PI, N. Butler) and UNAM. The agreement to continue the operation of



The RIMAS dewar assembled in the lab with the detector readout electronics attached.

the instrument has been extended for another two-year period.

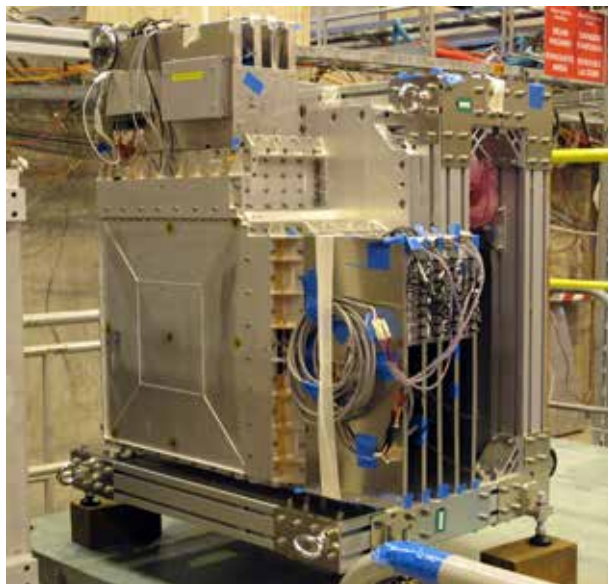
RIMAS (Rapid IMager-Spectrometer) is a joint project with the University of Maryland to develop an instrument for the Discovery Channel Telescope (DCT) at Lowell Observatory in Flagstaff. Goddard scientists are Kuttyrev, Cenko, Gehrels, and Moseley. RIMAS will have imaging and spectroscopic capabilities in the infrared region from $0.95\ \mu\text{m}$ to $2.4\ \mu\text{m}$. It will be used to follow up transient sources, including gamma-ray bursts and supernovae. The instrument is currently under construction. As part of the collaboration with Lowell Observatory, initial observations of GRB afterglows have been carried out with the existing DCT visible imaging camera.

SPACE STATION ATTACHED PAYLOADS

Calorimetric Electron Telescope (CALET)

CALET is a mission for the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station (ISS), manifested to fly on HTV-5 (H-II Transfer Vehicle 5) in summer 2015. CALET will measure the high-energy total electron spectrum into the trans-TeV energy range. These measurements have the potential to identify, for the first time, the signature of high-energy particles accelerated in a local astrophysical engine. Because electrons lose energy rapidly by synchrotron and inverse Compton processes, TeV electrons must have been accelerated within about 100,000 years and can have diffused at most a few hundred parsecs in that time. CALET will also search for signatures of dark matter annihilation in electron and gamma-ray spectra. Its measurements of cosmic ray nuclei from hydrogen to iron will extend into the region of the “knee” around 10^{15} eV to investigate possible structure and energy-dependent composition changes and to measure the ratio of secondary to primary cosmic rays. CALET will perform a gamma-ray all-sky survey, complementing Fermi and H.E.S.S. observations, to detect intense high-energy sources, study the diffuse component, and search for new regions of emission. CALET includes a low-energy (7 keV–20 MeV) gamma-ray burst monitor. GRB measurements are extended to high energy using the calorimeter.

In the CALET main telescope, a 27-radiation-length-deep imaging particle calorimeter provides energy resolution of a few percent and ex-



The engineering model of the CALET Main Telescope during the 2012 beam test at the CERN SPS. The zenith surface of the detector is pointed to the left in this picture to accept the incoming particle beam.

cellent separation between hadrons and electrons and between charged particles and gamma rays. Plastic scintillators measure particle charge and act as anticoincidence detectors for gamma-ray measurements. CALET is a JAXA project (PI, S. Torii, Waseda University) with researchers from Japan, Italy, and the U.S. (Louisiana State University, Goddard, Washington University in St. Louis, and the University of Denver). The ASD team of Mitchell, Hams, Krizmanic, Moiseev, and Sasaki are responsible for the instrument simulation, performance models, and accelerator testing and calibration. Krizmanic and Moiseev lead the U.S. simulation effort. Mitchell co-leads the accelerator tests.

ISS Cosmic Ray Energetics and Mass (ISS-CREAM)

The ISS-CREAM instrument is adapted from the balloon-borne CREAM payload and planned for launch to the JEM-EF on ISS using the SpaceX Dragon. ISS-CREAM will make direct measurements of cosmic-ray spectra from protons to iron to energies approaching the spectral “knee” around 10^{15} eV. These measurements will test models of cosmic ray acceleration and provide calibration data required to interpret ground-based air shower measurements. In addition, ISS-CREAM measurements of the energy-dependent abundance ratios of secondary cosmic-ray species to their primary progenitors will test models of cosmic ray transport and storage in the



The CREAM instrument during balloon inflation for an Antarctic flight.

galaxy. ISS-CREAM will also measure cosmic ray electrons into the TeV energy range, complementing CALET. ISS-CREAM uses a tungsten/scintillating-optical-fiber calorimeter to measure the energy of incident particles and silicon pixel detectors to measure particle charge. Scintillator-based detectors distinguish electron and hadron showers.

The ISS-CREAM collaboration includes the University of Maryland (PI, Eun-Suk Seo), Goddard, Pennsylvania State University, and Northern Kentucky University, as well as collaborators in Korea, France, and Mexico. ASD team members are Mitchell and Link. Goddard, Penn State, and Northern Kentucky University have sup-

plied the Boronated Scintillator Detector (BSD) for ISS-CREAM that measures neutrons to help distinguish high-energy electron cascades in the calorimeter from those initiated by protons. Because more neutrons are produced in hadronic cascades than in electromagnetic showers of the same energy, the neutron count is a sensitive discriminator to determine whether a shower was initiated by a hadron, such as a proton or atomic nucleus, or by an electron or gamma ray. The BSD was delivered on schedule and within budget and has been integrated into ISS-CREAM.

SUBORBITAL

Balloon-Borne Experiment with a Superconducting Spectrometer—Polar (BESS-Polar)

BESS-Polar uses a thin solenoidal superconducting magnet with a drift-chamber tracking system providing a large geometric acceptance for rare-particle measurements in long-duration balloon flights over Antarctica. Detectors to measure the charge and velocity of incident particles, time-of-flight scintillators and an aerogel Cherenkov counter form partial cylinders around the magnet. A middle time-of-flight layer within the magnet, below the tracker, reduces the threshold energy to about 100 MeV referenced to the top of the atmosphere. The collaboration is co-led by Goddard (Mitchell) and KEK



BESS-Polar II prepares for launch from Williams Field near McMurdo Station, Antarctica, in December 2007.

(High Energy Accelerator Research Organization, A. Yamamoto) and ASD team members are Mitchell, Sasaki, Sakai, and Hams. Analysis of BESS-Polar II data, taken during solar minimum in 2007/2008 shows that, within statistics, there is no evidence of primary antiprotons from evaporation of small primordial black holes as had been previously predicted. BESS data has also given an upper limit to the possible ratio of antihelium to helium of 6.9×10^{-8} , the most stringent limit to date. A new fine calibration of the spectrometer has been completed and high-precision BESS-Polar proton and helium measurements are nearing publication.

Super TransIron Galactic Element Recorder (SuperTIGER)

SuperTIGER measures the abundances of individual elements from 10Ne to 60Nd. High-statistics measurements from 30Zn to 40Zr will test and clarify the emerging model of cosmic ray origin in OB associations and models for atomic processes by which nuclei are selected for acceleration. SuperTIGER also measures the energy spectra of the more abundant elements 14Si to 28Ni at energies $0.8 \leq E \leq 10$ GeV/nucleon to search for features that microqua-

sars or other phenomena could superpose on the otherwise smooth energy spectra. The SuperTIGER collaboration includes Washington University in St. Louis (PI, W. Robert Binns), Goddard, Caltech, and JPL. The ASD team includes Mitchell, Brandt, Hams, Link, Sakai, and Sasaki.

SuperTIGER uses three layers of plastic scintillator and two Cherenkov detectors, one with an acrylic radiator and one with a silica aerogel radiator, to determine the charge and energy of incident nuclei. A coded scintillating optical fiber hodoscope gives area and path length corrections. Two independent instrument modules, each with a $1.16 \text{ m} \times 2.4 \text{ m}$ active area, give a total detection area of 5.4 m^2 and an effective geometry factor of $3.9 \text{ m}^2 \text{ sr}$ at 34Se (the heaviest element reported by the previous TIGER investigation) after nuclear interaction losses are considered. Goddard is responsible for the scintillators, Cherenkov detectors, and instrument mechanical structure and has led the instrumental calibration and analysis effort. Data from the SuperTIGER-1 flight show resolution at 26Fe less than 0.16e (where e is a unit electric charge) with clear peaks for every element up to 40Zr.

SuperTIGER-1 was launched on Dec. 8, 2012, from Williams Field, Antarctica. In about 2.7 circumnavigations of Antarctica, it flew for more than 55 days, setting duration records for heavy-lift scientific balloons. The instrument returned excellent data on over 50×10^6 cosmic-ray nuclei heavier than Ne. Because the SuperTIGER-1 flight was terminated very late in the Antarctic season at a distance of 1625 km from McMurdo, it could not be recovered in 2013. Recovery was attempted in 2013/2014 but the team was not able to reach the landing site due to changes in aircraft availability. A second recovery effort started in December 2014. SuperTIGER has been selected for a new SuperTIGER-2 flight in 2017.

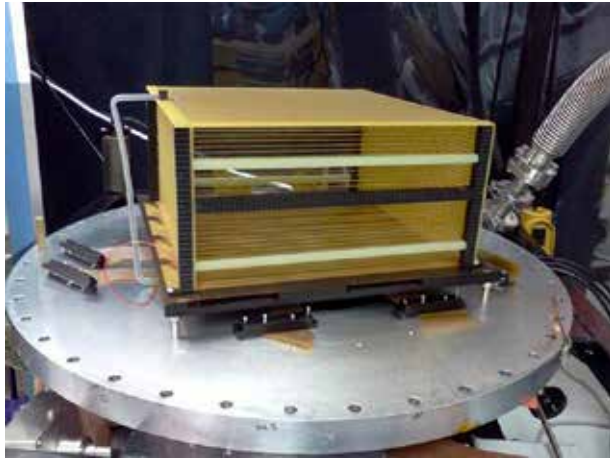


SuperTIGER-1 climbing out just after launch.

TECHNOLOGY DEVELOPMENT

Advanced Energetic Pair Telescope (AdEPT)

ASD's Hunter and Hanu continued development of the Three-Dimensional Track Imager (3-DTI) for the AdEPT gamma-ray polarimeter, a future gamma-ray telescope optimized for angular resolution and polarization sensitivity in the medium-energy (5–500 MeV) range. The 3-DTI, the enabling technology for AdEPT, is a large-volume time projection chamber (TPC) capable of three-dimensional track-



30 × 30 × 15 cm³ 3-DTI prototype; the 30 × 30 cm² MWD can be seen between the wires and supports forming the 15-cm tall drift volume. The flex-circuit connections between the MWD electrodes and the charge-sensitive front-end electronics have not been connected. The front-electronics and high-voltage supply for the drift grid are located below the aluminum plate.

ing and momentum measurement of charged particles. A two-dimensional micro-well detector (MWD) serves as a spatial readout and multiplication stage, while the third coordinate is obtained from the drift time of the primary charge through the gas volume. Each well of the MWD, 200 μm diameter on 400 μm centers, is an active gas proportional counter with gas gain of $\sim 10^4$. Negative ion drift is utilized to reduce the drift velocity and diffusion allowing for the large TPC volume.

Development of the 3-DTI technology has been slow due to limited funding. Nevertheless, we accomplished several goals advancing the AdEPT mission. These include:

- A hybrid (IDL/MDL) architecture study of the AdEPT mission was conducted with IRAD support. This study concluded that the 8 m³ baseline concept of the AdEPT mission is a viable mission, fitting well into the Explorer mission constraints.
- Teresa Sheets, with IRAD support, continued development of Tiler TILERcore-GX36-12 multi-core processor, for parallel processing of the gigabit per second streaming mode data expected from the AdEPT 1 m³ 3-DTI modules. The goals of this effort are to define the high data rate processing equipment and parallel processing methods for handling the onboard real-time, memory intensive processing of the Gb/s data stream to support the AdEPT instrument and other future scientific missions. Streaming mode data including the cosmic ray background expected for the 3-DTI operating in low Earth orbit has been simulated and tested with the Tiler hardware.
- The AdEPT team, expanded to include Krizmanic, Sheets, Stecker, Venters, Udayan Malik, and Andrey Timokhin, submitted a proposal titled *Development of the Three-Dimensional Track Imager for High Sensitivity Medium-Energy Gamma-Ray Polarimetry* to the APRA/ROSES program. This proposal was selected for four years of funding (FY15–FY18) to complete the 3-DTI development and to build and test a 50×50×100 cm³ AdEPT prototype
- A paper, “A Pair Production Telescope for Medium-Energy Gamma-Ray Polarimetry,” authored by Hunter, P. Bloser, G. Depaola, M. Dion, G. DeNolfo, M. Iparraguirre, J. Legere, M. McConnell, S. Nowicki, J. Ryan, S. Son, and Stecker, was published in *Astroparticle Physics* (59, 18–28, 2014).

X-ray Astrophysics Laboratory



Dr. Rob Petre
Lab Chief



Dr. Joe Hill-Kittle
Associate Lab Chief

Laboratory Overview

The scientists in the X-ray Astrophysics Laboratory (Code 662) conduct investigations of a broad range of astronomical systems through the detection and analysis of their X-ray emission and its relation to other radiations they emit. Objects studied range from nearby solar system objects to cosmological structures. Researchers investigate the physics of extreme environments such as those near the event horizons of black holes, as well as the evolution of stars, galaxies, and large-scale structures. The laboratory is the preeminent developer of state-of-the-art X-ray astronomical detectors and optical systems for performing precise spectroscopy, polarimetry, timing, and imaging. These instruments have been employed in numerous sub-orbital applications (sounding rockets and balloons) and orbiting observatories. In addition to a civil service staff of 21, the laboratory contains 65 university and contract scientists, engineers, technicians, postdocs, and grad students.

Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Simon Bandler	Low-temperature detectors, high-resolution X-ray spectroscopy	Athena X-IFU X-ray calorimeters	Systems Scientist
Megan Eckart	Low-temperature detectors, high-resolution X-ray spectroscopy, active galactic nuclei (AGN)	Astro-H SXS X-ray calorimeters	Calibration Scientist
Keith Gendreau	Pulsars, black holes, X-ray interferometry, diffractometers, cosmic X-ray background, X-ray spectroscopy	NICER/SEXTANT Astro-H SXS	Principal Investigator Co-Investigator
Joe Hill-Kittle	X-ray polarimetry, X-ray detectors, gamma-ray bursts	Swift PRAXyS	XRT Instrument Scientist Instrument Scientist
Ann Hornschemeier Cardiff	Accreting binary populations, starburst galaxies, AGN, clusters and groups of galaxies	Physics of the Cosmos Program Astro-H SXS NuSTAR ISS-Lobster	Chief Scientist Co-Investigator Science team member Co-Investigator <i>Johns Hopkins University</i>
Keith Jahoda	X-ray polarimetry, diffuse X-ray background	PRAXyS	Principal Investigator

Scientist	Research Interest	Project/Mission	Role/Affiliation
Tim Kallman	X-ray spectroscopy, polarimetry of accreting compact objects	Astro-H SXS PRAXyS	Co-Investigator Co-Investigator
Richard Kelley	X-ray astrophysics, imaging X-ray spectroscopy using X-ray calorimeters.	Astro-H SXS Athena X-IFU	U.S. Principal Investigator
Caroline Kilbourne	Low-temperature detectors, high-resolution X-ray spectroscopy, starburst galaxies, WHIM	Astro-H SXS Athena X-IFU X-ray calorimeters	Instrument Scientist Detector Scientist SAT, APRA PI
Maxim Markevitch	Clusters of galaxies, dark matter, X-ray imaging and spectroscopy, Sunyaev-Zeldovich effect	Astro-H	Science Advisor <i>JSI</i>
Craig Markwardt	X-ray binaries, X-ray polarimetry, pulsar timing, obscured AGN	NuSTAR Swift ISS-Lobster	Mission Scientist Co-Investigator
Takashi Okajima	X-ray mirrors, AGN, galaxy clusters, CZT Detectors	Astro-H SXS NICER InFOCuS	Soft X-ray Telescope Lead Instrument Scientist X-ray Concentrator Lead
Rob Petre	X-ray studies of supernova remnants, supernovae, pulsar wind nebulae and young stars, X-ray optics	Athena Astro-H SXS Suzaku ISS-Lobster	NASA Study Scientist SXS US Project Scientist Project Scientist Co-Investigator
Andy Ptak	Starburst galaxies, obscured AGN, galaxy evolution, and scientific software development	WFIRST-AFTA NuSTAR ISS-Lobster	Study Scientist GO Program Lead Co-Investigator <i>Johns Hopkins University</i>
Scott Porter	Astrophysical instrumentation, Laboratory astrophysics, soft X-ray background, charge exchange	Astro-H SXS Micro-X DXL NASA sounding rocket program Athena X-IFU	Instrument Scientist Institutional PI Institutional PI Deputy Project Scientist Co-Investigator
Peter Serlemitsos	X-ray spectroscopy, the X-ray background, SN remnants, clusters of galaxies, X-ray optics and detectors	Astro-H SXS	Co-Investigator Soft X-ray Telescope lead
Steve Snowden	Diffuse X-ray emission from the Milky Way, local ISM and solar wind charge exchange emission	XMM-Newton	U.S. Project Scientist
Tod Strohmayer	Physics of compact objects	NICER ISS-Lobster	Co-Investigator Co-Investigator <i>JSI</i>
Jean Swank	X-ray polarimetry, black holes, neutron star pulsars		Emeritus
Kim Weaver	AGN, starburst galaxies, accretion disks, ultraluminous X-ray sources	ASD Communications	<i>Johns Hopkins University</i>
Will Zhang	X-ray instrumentation (both optics and detectors), X-ray timing, compact objects, X-ray binaries	Lightweight and high-resolution X-ray optics, NuSTAR	SAT program PI

SCIENCE HIGHLIGHTS

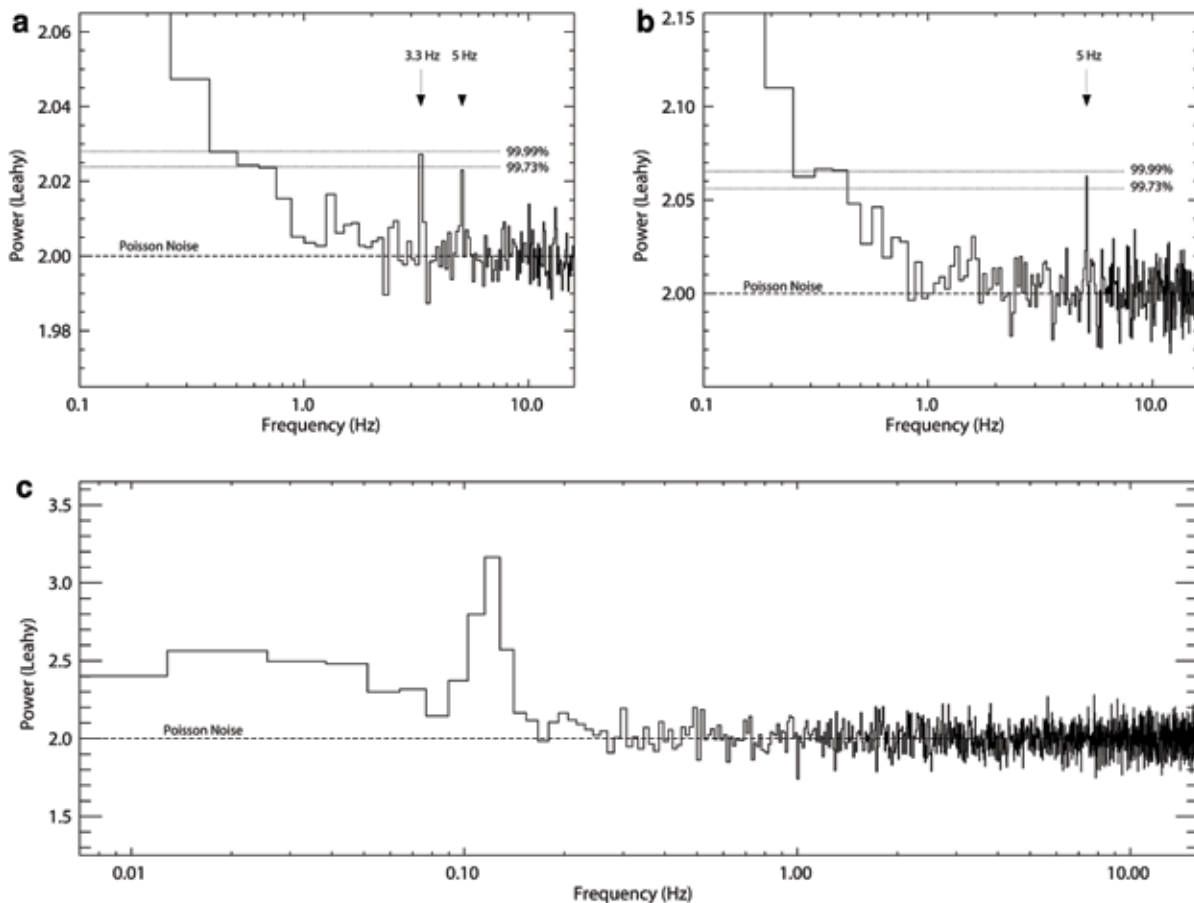
RXTE Decodes Rhythm of an Unusual Black Hole

Astronomers now know that the centers of most galaxies, including our own Milky Way, host super-massive black holes, often with masses millions to billions of times greater than our sun's. At the other extreme, studies of X-ray binaries have revealed the existence of stellar-mass black holes, formed in the spectacular supernova death of a massive star. Reaching a maximum of about 25 solar masses, these are relative "lightweights" compared to their supermassive brethren.

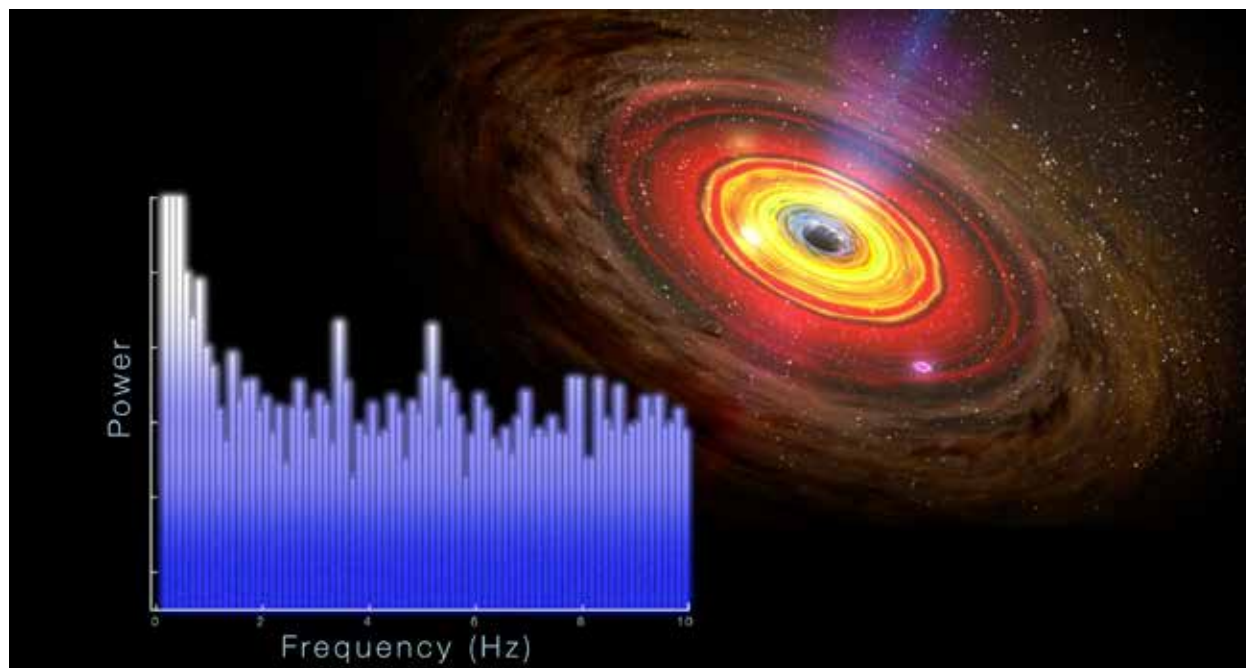
One of the current puzzles in astrophysics is how supermassive black holes got so massive so early in

cosmic evolution. Evidence indicates that some billion-solar-mass black holes formed much less than a billion years after the Big Bang. One avenue for rapid growth could be through mergers with smaller seed black holes of, say, a hundred or so solar masses. If so, then black holes resulting from such mergers should exist in the "middleweight" range between stellar and supermassive black holes. However, only a few such objects are known in this mass and their mass estimates are often quite uncertain. So the question remains, where are the middleweight black holes?

Ultraluminous X-ray sources (ULXs), a class of highly luminous objects in nearby galaxies, offer the potential to resolve this issue, as some of the brightest sources have been linked to the middleweight



Power spectra of M82. (a) Six-year average X-ray (3–13 keV) power density spectrum of M82 using 128-second ($\times 7362$) individual light curves. The two strongest features in the power spectrum occur at 3.32 ± 0.06 and 5.07 ± 0.06 Hz, consistent with a 3:2 frequency ratio. (b) Averaged power spectrum of all 1024-second ($\times 363$) segments. The strongest feature is at 5 Hz. (c) To facilitate a direct comparison with stellar-mass black holes, also shown is the broadband power spectrum of M82 (using ≈ 100 ksecs of XMM-Newton/EPIC data) showing the low-frequency QPO at 120 mHz in addition to the high-frequency QPO pair in the top panels. After Pasham et al (2014)



Artist's impression of the inner accretion disk around a black hole, where fast QPOs associated with orbital motions in the disk are produced. Inset: The power spectrum of X-ray flux variations for M82 X-1, showing stable 3:2-ratio QPOs at 5.1 and 3.3 Hz. Credit: NASA's Goddard Space Flight Center

mass range. To date, however, mass estimates have been too imprecise to be definitive.

The X-ray output of black holes is substantially variable, and the time over which these brightness variations occur traces the black hole's mass. Slower variations are produced by larger, more massive black holes, while higher frequency modulations reflect lower masses, analogous to the difference in tone between a bass violin and its standard-size cousin.

Quasiperiodic oscillations (QPOs) are a type of black hole variation whose frequencies provide a way to determine mass. A special class of high-frequency QPOs, which until recently have been seen only from stellar-mass black holes, occur in a 3:2 frequency ratio. For every three pulses of the faster QPO, a slower one produces two. In systems where they have been observed, the higher frequency QPO occurs at hundreds of cycles per second, and the QPO frequencies scale inversely with the known masses of these stellar black holes.

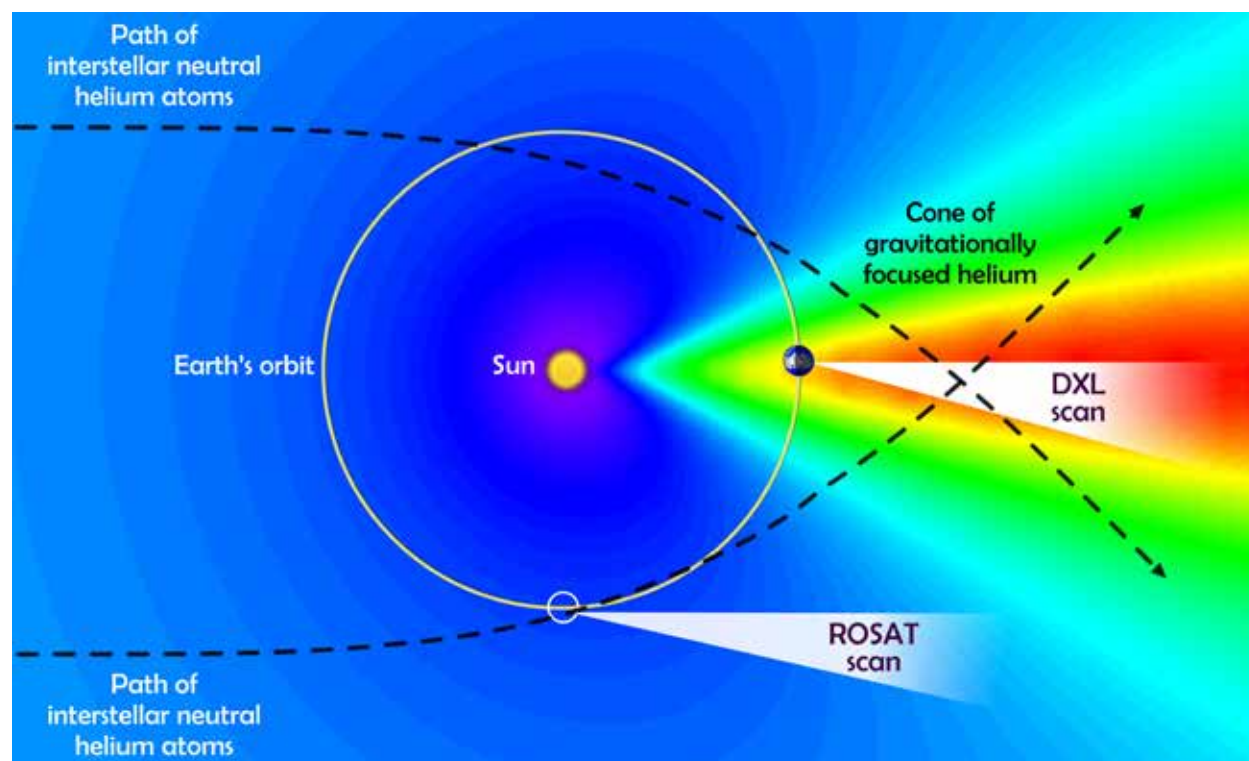
While QPOs have been seen in a few ULXs, one exhibiting a 3:2 ratio had never been observed. This changed when Dheeraj Pasham, Tod Strohmayer, and Richard Mushotzky found one in M82 X-1 (hereafter, X-1) after searching through 5.5 years of archival Rossi X-ray Timing Explorer data. This work represented a portion of Pasham's Ph.D. thesis, carried out under the co-sponsorship of Strohmayer and

Cole Miller at the University of Maryland, College Park, and was published in *Nature*.

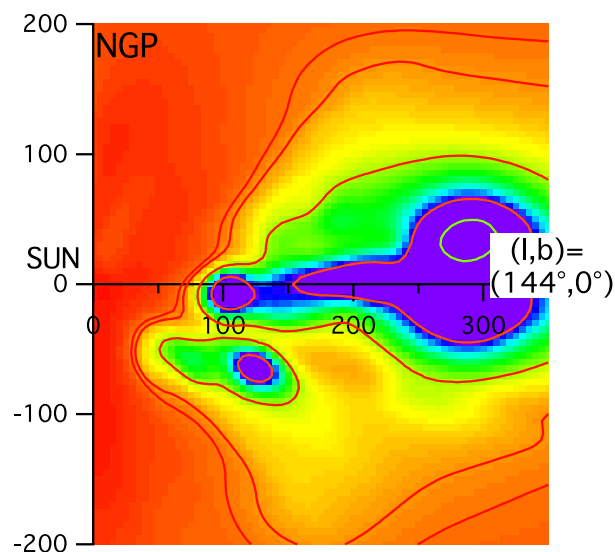
The team identified a pair of QPOs that reliably repeat at frequencies of 5.1 and 3.3 cycles per second, consistent with a 3:2 relationship. This is a substantially lower frequency than corresponding QPOs in stellar-mass black holes and is a strong indication that X-1 is more massive. By simply scaling by the observed ratio of QPO frequencies seen in stellar black holes to those seen in X-1, the team inferred the mass of X-1 to be in the range from 323 to 533 solar masses—a middleweight black hole. The finding suggests that other ULXs could have their black holes weighed in a similar fashion.

Resurrecting the Local Hot Bubble

The interstellar medium in the solar neighborhood is dominated by a neutral hydrogen cavity that extends ~50 light-years from the sun in the galactic plane and up to 500 light-years toward the galactic poles. The solar system currently lies within a diffuse, partially ionized cloud of limited extent, but for many years most of the cavity was thought to be filled with million-degree plasma. This came to be known as the Local Hot Bubble and was thought to be the origin for most of the observed $\frac{1}{4}$ keV diffuse soft X-ray background (SXRb).



Colors indicate the density of interstellar helium near Earth and its enhancement in a downstream cone as the neutral atoms respond to the sun's gravity (blue is low density, red is high). Also shown are the observing angles for DXL and ROSAT.



Map of the distribution of the neutral interstellar medium in the direction of $l\ 144^\circ\ b\ 0^\circ$, where purple indicates the denser material of the Local Cavity wall and distances are shown in parsecs. The inversion mapping is based on reddening and absorption line data and is currently limited by the number of sample stars to a resolution of $\sim 15\text{ pc}$. After Lallement et al. (2014).

In the early 2000s, this picture was called into question by the discovery that the solar system itself was a source of diffuse X-rays. These are produced by charge exchange between highly ionized metals in the solar wind, as well as by neutral hydrogen in Earth's exosphere and interstellar neutral hydrogen and helium flowing through the heliosphere. It was suggested that solar wind charge exchange (SWCX) could be responsible for all of the X-rays originating in front of the bounding galactic neutral hydrogen that defined the Local Cavity.

In order to resolve this controversy, ASD scientists devised an experiment to determine the SWCX flux by observing a feature resulting from the flow of interstellar gas through the solar system: the helium focusing cone, an enhancement downstream of the sun caused by gravitational focusing. For this experiment, neither high angular or spectral resolution were necessary, but a large effective area/solid angle product was vital. This led to a proposal to map the SXR by flying proportional counters built at the University of Wisconsin (supported by NASA grants) in the 1970s on a sounding rocket. The resulting project was named DXL, for Diffuse X-ray Emission from the Local Galaxy.

The instruments were refurbished at the University of Miami and flown in December 2012 on

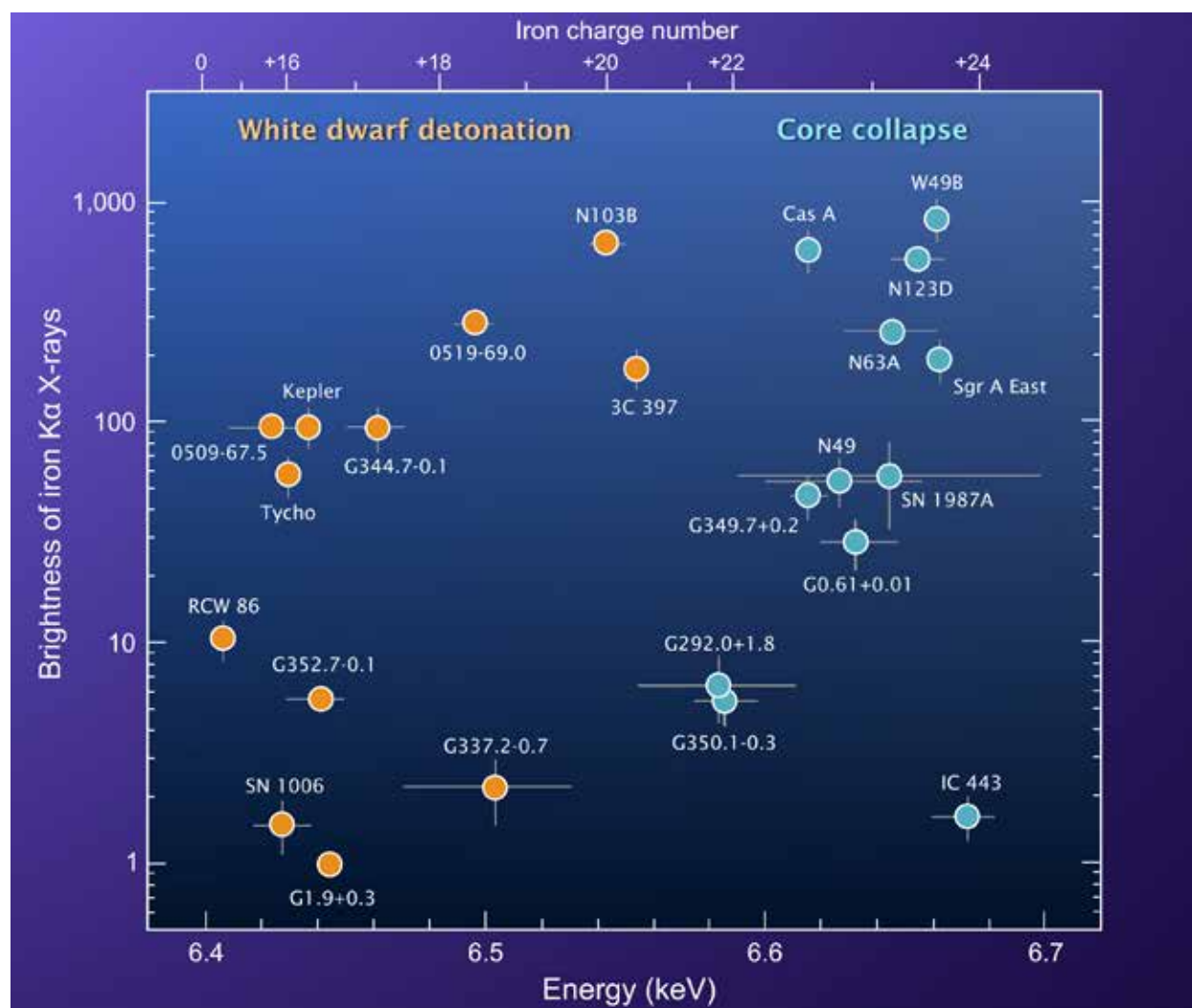
a NASA Black Brant IX sounding rocket launched from White Sands Missile Range. When the data were compared to the ROSAT map of the SXR (a project partially funded by NASA), the team identified a clear SWCX signal from the helium focusing cone. Based on these results, the team, which included ASD scientists Steven Snowden, Scott Porter, Nicholas Thomas and Meng Chiao, determined that only about 40 percent of the observed flux in the galactic plane originated within the heliosphere. Because the walls bounding the Local Cavity are optically thick at $\frac{1}{4}$ keV, the remainder of the observed emission must originate from inside it. This finding, which confirms the existence of the Local Hot Bubble, was published in *Nature* in August 2014.

Additional support for this interpretation comes from an ASD analysis that combines the sounding

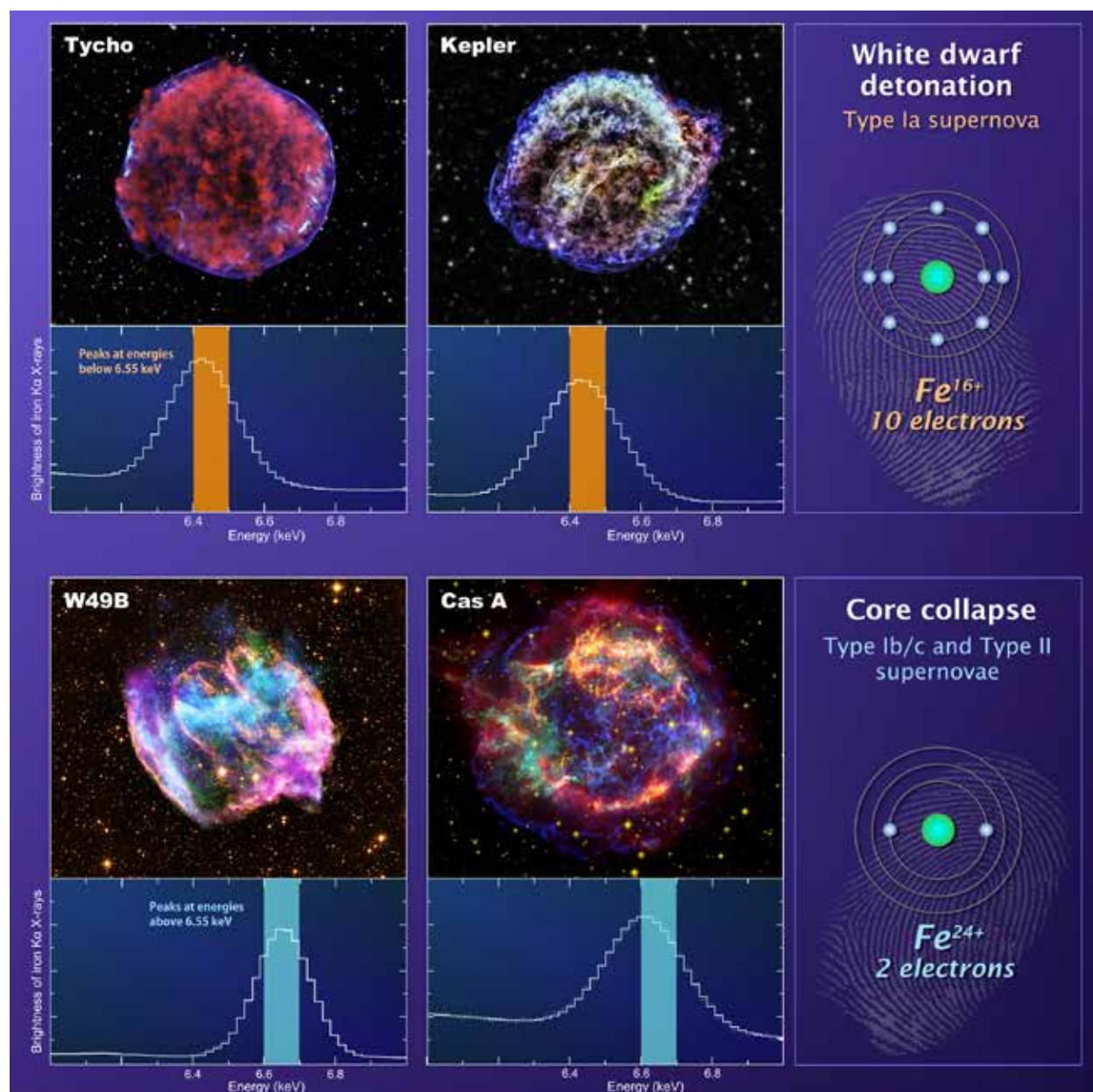
rocket results with Voyager observations of the interstellar magnetic field within the cloud surrounding the solar system and with interstellar absorption line measurements that determined the extent of the Local Cavity. Assuming that hot plasma fills the entire path length between the local cloud and the cavity edge, the team determined that the plasma's thermal pressure is in equilibrium with the thermal plus magnetic field pressure of the local cloud. With this determination, the Local Hot Bubble model is now consistent with all current observations.

Iron “Fingerprints” Distinguish Supernova Remnants

Using Suzaku, the fifth in a series of Japanese X-ray astronomy satellites cooperatively operated by the



Plotting supernova remnants with known or candidate explosion types by their peak iron K-alpha energy reveals a clear division between those created by core-collapse and type Ia explosions. Gray lines indicate error bars. Credit: NASA's Goddard Space Flight Center



Suzaku observations of 23 supernova remnants, including those shown here, reveal a distinction between those from massive stars and those from white dwarfs. The peak X-ray energy from the so-called K-alpha emission line of ionized iron serves as a fingerprint to quickly identify the explosion source. Credit: NASA's Goddard Space Flight Center

U.S. and Japan, ASD's Hiroya Yamaguchi studied 23 well-known supernova remnants in the Milky Way and in the Large Magellanic Cloud. He and his colleagues revealed that the peak energy of the iron K-alpha line, which is produced when electrons drop from the L shell to the K shell, clearly separate core-collapse and type Ia supernova remnants, with the latter generally having a lower peak energy of this emission. Within each group, the iron K-alpha luminosity and peak energy have a positive cor-

relation. The technique provides a clear and rapid means of classifying supernova remnants and constraining the star's pre-explosion environment.

Supernova remnants provide unique insights into both the explosion that generated them and the environment surrounding the star before its destruction. However, the complex physical processes involved in the interaction between ejecta and the ambient medium often blur this information, so

much so that the explosion type of several well-studied remnants remains controversial.

Supernovae fall into two broad classes based on the triggering event. Those called core-collapse supernovae occur in stars born with more than eight times the sun's mass when they undergo a terminal energy crisis, collapse under their own weight and explode. The other variety, known as type Ia supernovae, occurs when white dwarfs explode in a runaway thermonuclear reaction. Type Ia supernovae are so bright they can be detected across the observable universe and led astronomers to discover that the expansion of our universe is accelerating.

Stars produce outflows of gas, called stellar winds, throughout their energy-producing lives, and the strongest winds are created by massive stars. When such a star explodes, its ejecta interact with previous outflows, reaching higher temperatures and imprinting the signature of more highly ionized iron atoms onto the remnant. White dwarfs are associated with less intense stellar winds, so type Ia supernovae explode into a cleaner environment. By interacting with less circumstellar material, type Ia remnants don't heat up as much and therefore contain cooler, less ionized iron atoms. Supernova remnants therefore retain a memory of their surroundings, allowing astronomers to probe the pre-explosion environment of supernovae out to several light-years.

The full potential of the new method will be realized with larger samples of higher-quality data expected from upcoming X-ray missions such as Astro-H, scheduled to launch in early 2016. Studying large samples of X-ray-emitting supernova remnants in nearby galaxies will dramatically increase our understanding of both classes of stellar explosion.

PROJECTS IN DEVELOPMENT

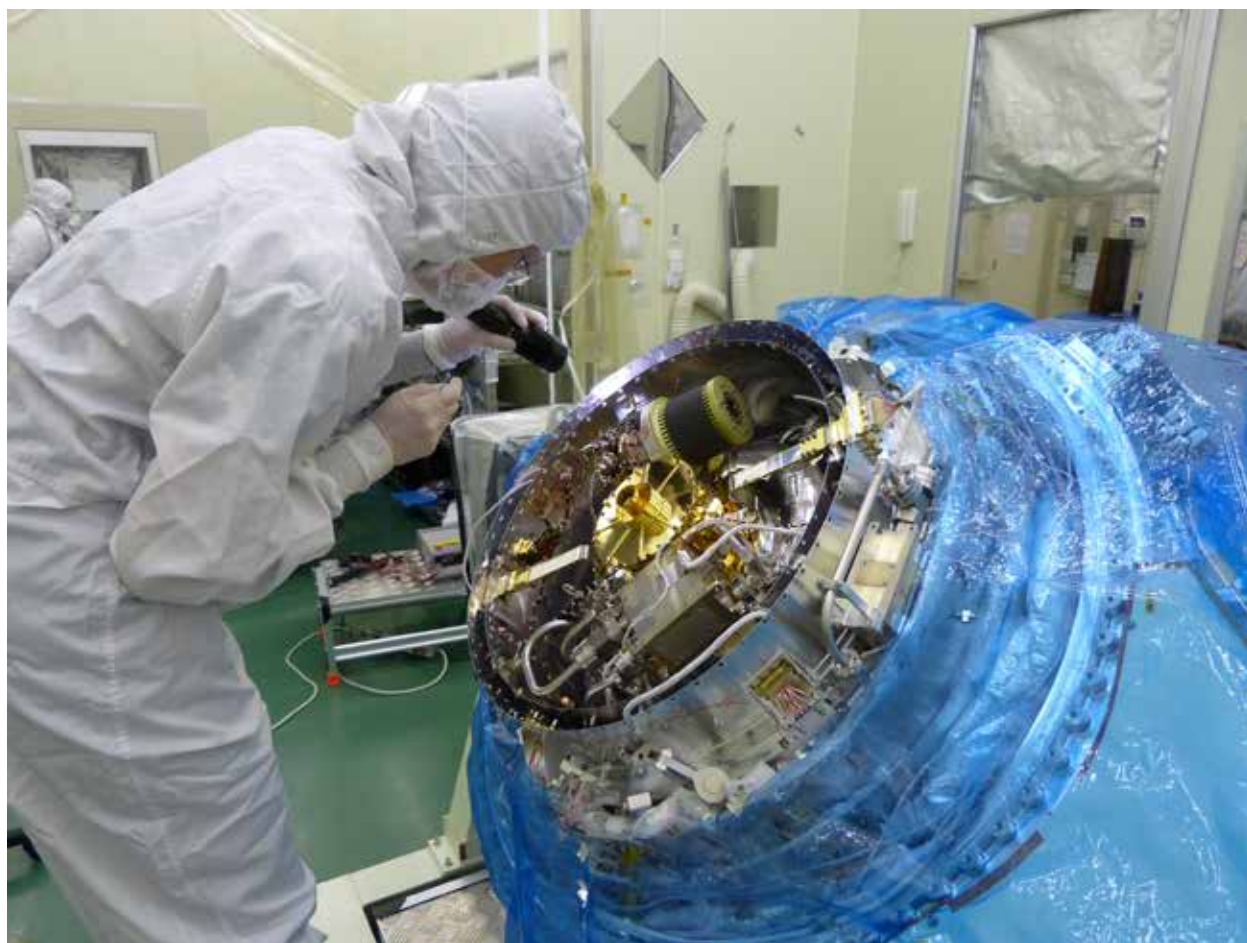
ASTRO-H

The X-ray Astrophysics Laboratory is collaborating with ISAS/JAXA to implement an X-ray calorimeter spectrometer for the Astro-H mission. The project, headed by Kelley, is implemented as an Explorer Program Mission of Opportunity to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments. Among laboratory scientists, Chiao, Kilbourne, and Porter are responsible for the detector subsystem, and Serlemitsos and his team of Okajima and Soong are responsible for X-ray mirrors for both the SXS and the ISAS/JAXA Soft X-ray Imager (SXI). Eckart and Leutenegger are developing the calibration program for the detector system. Dan McCammon of the University of Wisconsin, a long-term collaborator with the X-ray Astrophysics Laboratory and a pioneer in X-ray calorimeters, is developing a new generation of blocking filters for the instrument. Petre is the U.S. Project Scientist for Astro-H.

The Astro-H Soft X-ray Spectrometer (SXS) will consist of a 36-pixel X-ray calorimeter array with better than 7-eV resolution to provide high-resolution X-ray spectroscopy over the 0.3–12 keV band with moderate imaging capability. The Goddard team is to provide the detector system, adiabatic demagnetization refrigerator (ADR, with a 50 mK operational temperature), electronics, aperture components and blocking filters, and X-ray mirror, while ISAS/JAXA is responsible for the dewar system, other SXS electronics and the rest of the science payload, the spacecraft, launcher, and mission operations. The Space Research Organization of



Scott Porter and Meng Chiao (front left and right) assist with the installation of the flight SXS Calorimeter Spectrometer Insert into the flight dewar.



Caroline Kilbourne inspects the completed forward end of the SXS dewar prior to the next phase of close out and aperture installation.

the Netherlands (SRON) is separately providing to JAXA a filter wheel and in-flight calibration sources.

The dewar is a hybrid cryogen/mechanical cooler system for redundancy, and the X-ray mirror will build on the Goddard legacy of providing lightweight high-throughput mirrors.

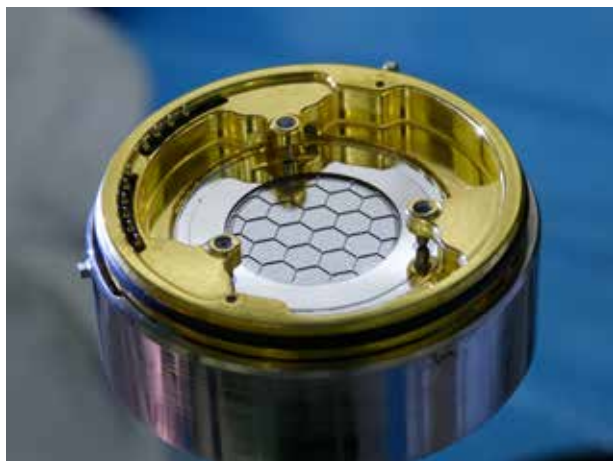
Astro-H is a facility mission to be launched on a JAXA H-IIA into low Earth orbit in late 2015. Its objectives are to trace the growth history of the largest structures in the universe, provide insights into the behavior of material in extreme gravitational fields, determine the spin of black holes and the equation of state of neutron stars, trace shock-acceleration structures in clusters of galaxies and supernova remnants, and to investigate the detailed physics of jets. Achieving these objectives requires the SXS and three additional scientific instruments to provide a very broad, simultaneous energy bandpass. The Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5–80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends the Astro H energy band to 600 keV, and the

Soft X-ray Imager (SXI) expands the field of view with a new-generation CCD camera.

The SXS science investigation comprises building and delivering the SXS instrumentation and carrying out a six-month observing program in collaboration with ISAS/JAXA. The baseline mission includes two years of funding for the SXS science team and support for processing and archiving the SXS data for a total of three years. An approved Science Enhancement Option (SEO) will provide the U.S. community with access to Astro-H beyond the baseline program. Under the SEO, U.S. scientists will be able to propose for Astro-H observing time and obtain grant support.

Working collaboratively with JAXA, the U.S. Guest Observer Facility will process, distribute, and archive data from all four Astro-H instruments, and provide observers with analysis tools and support. Angelini is leading the design and development of this program.

Major activities and milestones have been accomplished this year. All of the flight hardware com-



One of the four filters to be installed in the SXS dewar developed jointly by Goddard, the University of Wisconsin, and Luxel Corporation. This filter consists of a silicon wafer etched to form a mesh that has both a fine and coarse grid for strength. The large hexagonal pattern has a pitch of 5.3 mm, while the fine grid has a pitch of 330 microns. The filter mesh supports a polyimide film with an aluminum layer, each about 1000 angstroms thick. These filters are required to reject light with energies lower than about 0.3 keV that would otherwise create noise or thermally overwhelm the calorimeter array. The Si wafer is held within a three-point kinematic mount to eliminate thermal mechanical stress that could otherwise cause the wafer to shatter when cooled. The other side of the filter has heaters and thermometers for defrosting, if necessary.

ponents developed at Goddard have been delivered to Japan, incorporated into the JAXA hardware, and tested. The instrument has been operated on numerous occasions starting in October 2014. The intrinsic performance of the detector system is excellent, with an energy resolution of 4.5 eV across the array. When tested with the Stirling cycle cryocoolers running at nominal power, however, the resolution was found to be up to 100-percent worse and variable, depending on other details of the dewar state. This was attributable to mechanical vibrations causing time-variable heating of the 50 mK detector stage, which needs to be very stable. Fortunately, the JAXA SXS team pursued mechanical isolators designed to be installed between the cooler compressors and the dewar, and these turn out to work extremely well. With the isolators installed, the energy resolution performance is essentially identical to what was measured in subsystem level tests at Goddard and is stable.

All of this work was carried out with numerous, often lengthy, trips to Japan by the instrument team



Caroline Kilbourne and Sam Moseley install one of the SXS filters. The operation is performed inverted to prevent anything from falling into the dewar. Each filter is installed with a custom tool developed by Moseley that is designed to minimize stress and the generation of potential debris that could cause the filters to fail during launch.

from the X-Ray Astrophysics Laboratory (Chiao, Eckart, Kelley, Kilbourne, Leutenegger, Porter, and Watanabe). The team also supported subsystem vibration tests and calibration in Japan. This was all done while also running subsystem-level calibration measurements of the spare detector system at Goddard.

Both X-ray mirrors have been extensively characterized and calibrated in Japan and exceed their requirements for collecting area and imaging performance. In particular, the point spread functions of both mirrors is ~ 1.2 arcmin, which is a significant improvement over the ~ 2 arcmin of the Suzaku mirrors.

A summary of the top-level instrument performance characteristics is given in the table. *All of the key performance areas of the instrument exceed the requirements set forth in the proposal back in 2008.* Another key feature of the SXS is that it is designed to operate with and without liquid helium. The cryogen mode (with liquid helium) is

the default initial mode, and should last for about four years after launch. The cryogen-free mode also works well and should last as long as the mechanical coolers continue to operate (nominally many years). This is the first time a cryogen-free X-ray calorimeter spectrometer qualified for spaceflight has been demonstrated and operated, and it is the basis for future missions such as Athena.

Astro-H instrument performance characteristics		
Parameter	Requirement	Measured
Energy resolution	7 eV (FWHM)	4.5 eV
Energy accuracy	± 2 eV	± 0.5 eV
Residual background	1.5×10^{-3} counts/s/keV	same
Angular resolution	1.7 arcmin	1.2 arcmin
Effective area (1 keV)	160 cm ²	250 cm ²
Effective area (6 keV)	210 cm ²	312 cm ²
Cryogen lifetime	3 years	4 years

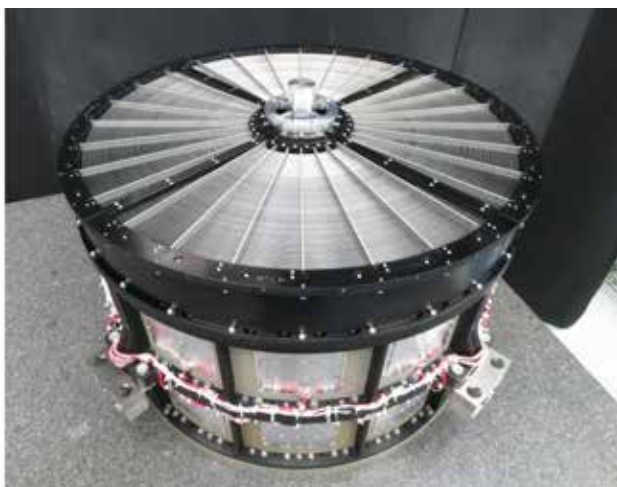
The Astro-H hardware teams were recognized by several awards. The Astro-H Soft X-Ray Telescope team received both a NASA Agency Award and Robert H. Goddard Exceptional Achievement Award for the development and timely delivery of the Astro-H Soft X-ray Telescopes, with performance exceeding mission goals, while the Astro-H



The finished SXS dewar undergoing vibration testing at the Tsukuba Space Center in Japan.

Soft X-Ray Spectrometer instrument team received a NASA Agency Award for the successful completion of the Astro-H Soft X-Ray Spectrometer flight hardware.

The next steps are full testing at the spacecraft level, a comprehensive thermal-vacuum test of the observatory, mechanical vibration, final performance tests, and shipping the observatory to the



The X-ray mirrors produced for the Astro-H Soft X-Ray Imager (left) and SXS (right). The mirrors have 203 concentric reflectors, so contain 1624 individual, precisely aligned mirror segments. They are 45 cm in diameter and have a mass of 43 kg each.

Tanegashima launch complex in autumn 2015 for an anticipated launch in early 2016.

The Astro-H Science Enhancement Option includes activities related to data analysis, the Guest Observer (GO) program and user support. To manage and implement these activities, Angelini is directing the Astro-H U.S. data center at Goddard that includes members Krimm, Loewenstein, and Yaqoob, who are working closely with the instrument teams at Goddard and in Japan. The pre-launch activities are focused on pipeline data processing, instrument software, collection of calibration information and preparing the necessary documentation and simulation software to support the GO program for all four Astro-H instruments. The Astro-H U.S. data center will be the liaison between GOs and the Astro-H program, with a help desk that will open at times near launch.

Finally, the larger Astro-H international science team is busy planning for launch operations and initial observations. To prepare for this, the team has written and published 17 white papers on arXiv.org that describe the science scope that will be addressable using Astro-H, and the team is now reviewing specific target proposals from within the team for the first six to nine months of the mission. The Announcement of Opportunity for the general community will be released several months after launch.

PROJECTS IN OPERATION

Suzaku (Astro-E2)

Suzaku is the fifth in a series of Japanese X-ray astronomy satellites, launched by the Japan Aerospace Exploration Agency (JAXA) on July 10, 2005. Like ASCA before it, Suzaku is a joint Japan-U.S. mission, developed by JAXA's Institute of Space and Astronautical Science (ISAS) in collaboration with Goddard and many other institutions.

Suzaku's operational scientific payload includes two co-aligned instruments. The X-ray Imaging Spectrometer (XIS) consists of four imaging CCD cameras (three working) sensitive in the 0.3–10.0 keV band, each located at the focal plane of a dedicated X-ray telescope (XRT). The second is a non-imaging, collimated Hard X-ray Detector (HXD) sensitive in the 10–600 keV band. The X-ray Spectrometer (XRS) stopped working shortly after launch as the result of a spacecraft design error.

As the tenth anniversary of launch approaches, age-related power system problems have forced reduced operations. The steady decline of solar panel power output has continued. Additionally, both batteries have experienced cell failures; the current operational mode utilizes the reliable cells from both. The available power is no longer adequate to operate both instruments on a regular basis. Thus the HXD is switched off for most observations. It is hoped that Suzaku can continue to operate into early 2016, to provide overlap with Astro-H for cross calibration.

After supplying key flight hardware (key components of the XRS, plus five XRTs), Goddard's current role is operating the U.S. Suzaku Data Center. The Data Center is responsible for maintaining the data processing pipeline; processing and archiving the full mission data set and distribution of data to U.S. Guest Observers (GO); development and maintenance of proposal and observation planning tools and documentation; maintaining the calibration database; supporting U.S. proposal reviews; and assisting GOs in analyzing data. The data center staff consists of three full-time scientists (Mukai, Hamaguchi, and Pottschmidt) and one programmer, plus part-time support from HEASARC staff. Rob Petre is the NASA Project Scientist and Lorella Angelini is the Deputy Project Scientist.

The 2014 NASA Senior Review recommended that funding be continued for Suzaku through 2016, and recommended increased funding to allow the creation of an archival catalog.



The merging galaxies Arp 299. NuSTAR data are shown on the left, a visible light image from NASA's Hubble Space Telescope is shown at right. The center panel overlays the NuSTAR data onto the Hubble image. Red represents X-rays with energies of 4 to 6 keV, green shows energies of 6 to 12 keV, and blue indicates 12 to 25 keV X-rays. The observation show that the supermassive black hole in the galaxy at right is releasing energetic X-rays as it consumes gas. Credit: NASA/JPL-Caltech/GSFC

Suzaku has produced an abundance of results from a wide variety of cosmic X-ray sources. Prominent recent examples:

- A comprehensive analysis of all supernova remnants observed by Suzaku shows the ionization state of iron in SNRs arising from thermonuclear (Type Ia) supernovae are systematically lower than that in SNRs from core-collapse explosions. This difference arises from the fact that core-collapse remnants expand into a denser local medium, significantly altered by pre-supernova mass loss, and provides the cleanest way of distinguishing the two types of remnant.
- Suzaku observations show that gas flowing out at a quarter the speed of light from the central supermassive black hole in the Ultraluminous Infrared Galaxy IRAS F11119+3257 is physically connected to a molecular outflow at a large distance from the nucleus. The total mass removal rate of ~ 800 solar masses is sufficient to stifle star formation near the center of the galaxy.

Suzaku detected a substantial abundance of the rare metals Mn and Ni in the spectrum of the thermonuclear (Type Ia) supernova remnant 3C 397. Only so-called “single degenerate” explosion scenarios can produce the high density needed in the progenitor core to synthesize these metals. As the “double-degenerate” scenario accounts for much of the phenomenology in other Type Ia SNe, this result suggests the existence of multiple Type Ia explosion mechanisms.

Nuclear Spectroscopic Telescope Array (NuSTAR)

Launched in June 2012, NuSTAR is a Small Explorer mission designed to observe the X-ray sky in the 3–80 keV band with unprecedented combined image and spectral resolution. NuSTAR is led by Principal Investigator Fiona Harrison at Caltech and managed by JPL with Goddard oversight by Mission Scientist Craig Markwardt.

Goddard contributed nearly 7,000 thin glass substrates, which are the foundation of the innovative multilayer X-ray mirrors manufactured and tested by a team led by Zhang. While standard monolayer X-ray mirrors are not reflective above 10 keV, NuSTAR's multilayer mirrors have sensitivity area up to 80 keV. NuSTAR's combination of X-ray collecting area (800 cm² at 10 keV), imaging resolution (58" half-power diameter), and broadband energy coverage enable the study of cyclotron lines from X-ray pulsars, the detection of Compton reflection from accreting black holes, the observation of nucleosynthesis in supernova remnants, and enable a deep hard X-ray survey to find highly obscured sources not detectable in other wavelength bands. ASD scientists participate on the NuSTAR science team, including Hornschemeier, Lehmer, Markwardt, Pottschmidt, Ptak, Rigby, Teng, Wik, and Yukita.

In 2014, NuSTAR continued smooth operations. In August, the NuSTAR project completed its baseline mission. The science team completed all of its five Level 1 scientific requirements during this period. Anticipating completion of the baseline mission, NuSTAR participated in the NASA Senior Review process in early 2014 and was very highly

ranked against other astrophysics missions. NASA Headquarters directed NuSTAR to extend operations for an additional 2-4 years, with a re-evaluation in 2016.

A major new component of the extended operation phase is a Guest Observer program, which allows members of the scientific community to propose dedicated observations of their requested targets. A fraction of 50 percent of NuSTAR's total observing time is available for guest observers. On behalf of NASA Headquarters, ASD scientists Ptak and Markwardt oversee the implementation of the program, including input to the design of the announcement, providing documentation, recommending panels and panelists, and management of guest observer grants. The announcement of opportunity was released to the international community in August 2014, with proposals due in November, for a total of 7.5 Megaseconds of available time and \$1.5 million of grants for U.S. principal investigators. NuSTAR also offered Suzaku observing timing as a part of the NuSTAR review process. NuSTAR received a tremendous response to the call — over 193 proposals, which amounted to an oversubscription by a factor of six to the available resources. Based on the response, the GO program anticipates six review panels to handle the load of proposals. Proposals are to be evaluated in 2015 based on competitive review by scientific peers. NuSTAR also competitively grants approximately 2 Megaseconds of observing time in conjunction with the XMM-Newton and Chandra proposal calls.

The NuSTAR public science data archive is hosted at Goddard's HEASARC. Since opening in 2013, the number of data sets available to the public has nearly doubled to 643. The amount of NuSTAR archive downloads in 2014 nearly quintupled over the previous year. This is partly due to interest in the call for proposals, due in late 2014. NuSTAR also continues to release improved calibration and software products.

In 2014, Ptak and collaborators published new NuSTAR and Chandra observations of the Arp 299 colliding galaxy pair. NuSTAR has revealed that the black hole located at the right of the pair is actively gorging on gas, while its partner is either dormant or hidden under gas and dust. NuSTAR is the first telescope capable of pinpointing where high-energy X-rays are coming from in the tangled galaxies of Arp 299. Previous observations from other telescopes, including NASA's Chandra X-ray Observatory and the European Space Agency's XMM-Newton, which detect lower-energy X-rays, had indicated the presence of active supermassive black holes in Arp 299.

However, it was not clear from those data alone if one or both of the black holes was accreting.

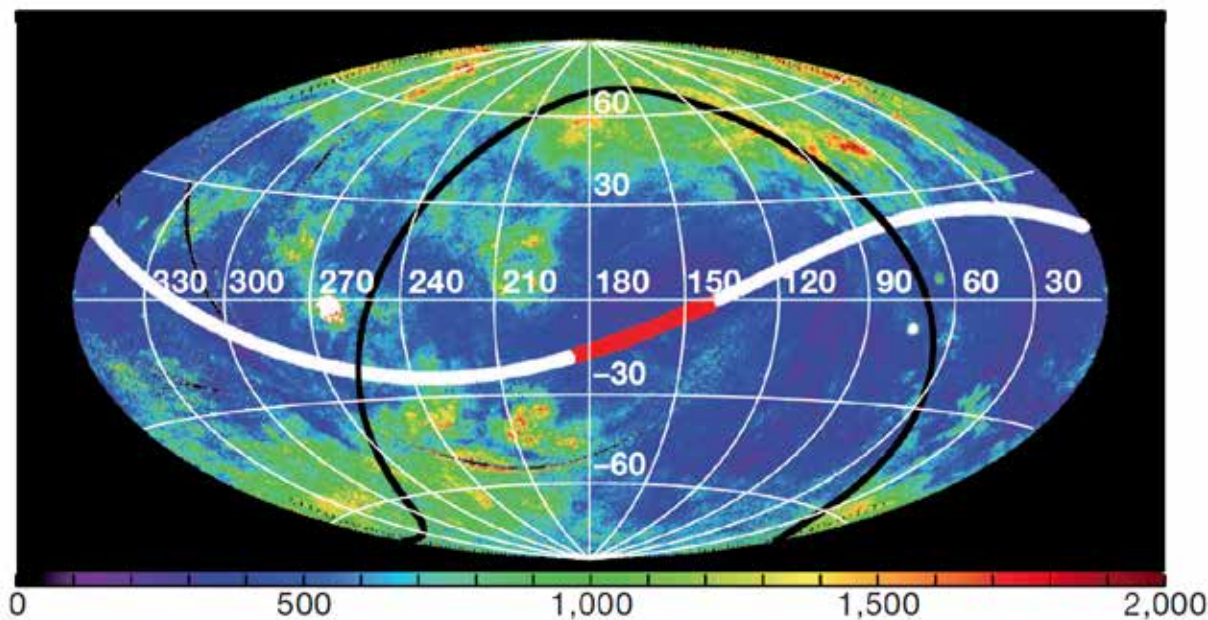
The findings are helping to understand how the galaxy mergers can trigger black holes to start feeding, an important step in the evolution of galaxies. When galaxies collide, gas is sloshed around and driven into their respective nuclei, fueling both star formation and the growth of black holes. NuSTAR is ideally suited to study heavily obscured black holes such as those in Arp 299. High-energy X-rays can penetrate the thick gas, whereas lower-energy X-rays and light are blocked.

XMM-Newton Guest Observer Facility

ASD operates the U.S. XMM-Newton Guest Observer Facility (XMM GOF). XMM is an ESA X-ray astrophysics mission with some U.S. hardware and software contributions. ESA allocates resources to support European XMM users but looks to the GOF to provide support to the large U.S. astrophysics community. GOF activities include facilitating the submission of GO proposals to ESA, distributing proprietary data to U.S. PIs, maintaining the full public science archive, and supplying expertise, analysis software and documentation to U.S. scientists. The GOF also runs a Guest Observer grant program funding 30 to 35 programs each observation cycle.

The GOF works in conjunction with the ASD GOFs of other high-energy astrophysics missions (e.g., Fermi, Swift, and Suzaku) to lower costs and to ensure consistency in the areas of the budget proposal process, FITS tools, database structure, web pages and archival data access. Cost savings are leveraged by sharing resources, techniques, expertise and reusing software. GOF activities cover a very wide range of endeavors in support of XMM. This year, the GOF's duties included: continuing to develop software for the analysis of extended sources; updating the Optical Monitor Catalog (OMCat); updating the popular ABC and D Guides with the new SAS releases; continuing development of Perl script "wrappers" to streamline data reduction for non-experts; continuing to maintain the XMM bibliography (now ~4,000 refereed papers over the mission's lifetime); and continuing development of Trend-data tools.

The XMM GOF was successful in the 2014 Senior Review process with continued funding for GOF operations through FY16, including strongly enhanced Guest Observer funding. The GOF will submit a proposal to the 2016 Senior Review for continued funding through 2018.



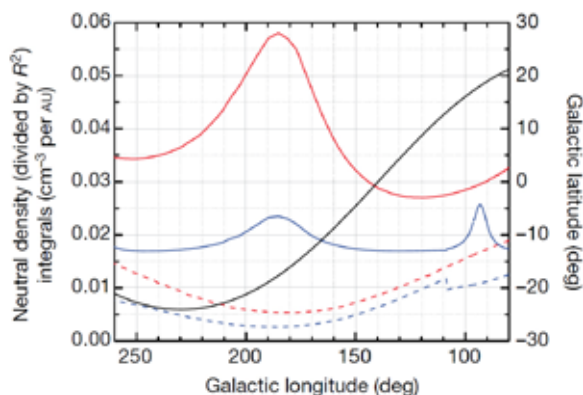
The DXL scan path overlaid on a ROSAT image of the soft (1/4 keV) X-ray sky. The red portion is the slow scan on and off the He focusing cone, which was repeated four times. The white portion is a fast scan that encompassed an Earth eclipse to monitor the local non-X-ray background. The slow scan path was selected to coincide with a featureless, low flux region of the soft X-ray sky.

SOUNDING ROCKET PROGRAM

Diffuse X-ray Emission from the Local Galaxy (DXL)

The project uses an old payload repurposed for new science. It is now widely believed that a significant component of the soft X-ray background results from the interaction of the solar wind with neutral atoms within our solar system. Observing from low Earth orbit, we have seen significant emission from the solar wind interacting with exospheric neutral hydrogen (magnetospheric emission), and also the solar wind interacting with interplanetary hydrogen and helium (heliospheric emission). These two sources have very different spatial and temporal signatures, but are both the result of charge exchange recombination, where a highly ionized solar wind ion removes an electron from a neutral species, emitting photons, including X-rays, as it relaxes to its ground state. The DXL payload contains two 800 cm² proportional counters built in the late 1970s at the University of Wisconsin to map the soft X-ray background. However, DXL uses the same large-grasp instrument to spatially disentangle the heliospheric charge exchange emission from more distant sources of soft X-ray emission, such as the Local Hot Bubble, and compare the results to modern spatial and temporal models of solar wind charge exchange.

The DXL project brings together scientists from several disparate fields. ASD scientists include Porter, Snowden, Kuntz, Chiao, and Thomas, who have a strong interest in the soft X-ray background and in understanding the solar wind charge exchange contamination of many soft X-ray observations with ROSAT, Chandra, XMM, Suzaku, and soon, Astro-H. This is in partnership with Goddard



Combined Counter-I and Counter-II count rates (black dots) during the DXL scan and the ROSAT 1/4 keV count rate in the same directions (blue solid line). The best fit to the DXL total count rate (red solid line), and the solar wind charge exchange contribution to DXL (red dashed line) and ROSAT 1/4-keV bands (blue dashed line) are also shown.

collaborators Sibeck (Space Weather Laboratory, Heliophysics Science Division) and Collier (Solar System Exploration Division), who study the interaction between the solar wind and Earth's exosphere to understand the critical boundary layer that drives much of space weather. The PI institution is the University of Miami, with the University of Kansas, the University of Wisconsin, and Leicester University as collaborating institutions.

The DXL payload also includes a Goddard-provided instrument, STORM, as a technology demonstration. STORM is a microchannel-plate X-ray detector with a wide field of view (10×10 degrees) lobster-eye slumped microchannel-plate optic. This is a prototype instrument for a full-scale magnetospheric charge exchange X-ray imager, and DXL is the first space-flight demonstration of this technology. The STORM instrument was developed at Goddard by ASD scientists Porter, Snowden, Kuntz, Chiao, and Thomas, with collaborators Collier, Sibeck, and the University of Leicester.

The DXL and STORM payloads successfully flew on Dec. 12, 2012. DXL clearly observed charge exchange from interplanetary helium in the helium focusing cone and fully constrained the charge exchange contribution to the Local Hot Bubble. The scan path for the DXL flight was selected to cross a flat, relatively low-emission region of the soft X-ray sky. STORM also clearly observed cosmic soft X-ray emission. Both instruments performed flawlessly and landed without damage.

The next flight of DXL will add a third energy band proportional counter and is scheduled for December 2015. A Cubesat version of STORM also will fly as a secondary payload as part of the mission. A third flight of the instrument is planned for 2016, where it will fly from Poker Flats, Alaska, to observe charge exchange in the cusps of the magnetosphere.

Micro-X

The Micro-X sounding rocket experiment is designed to be the first X-ray calorimeter payload using focusing X-ray optics. It uses significant design heritage from the XQC program, including a very similar adiabatic demagnetization refrigerator, however the detector and readout technology derive from the IXO program. The ASD research team includes Porter, Kelley, Kilbourne, Bandler, Adams, Eckart, Smith, Serlemitsos, and Soong. Collaborating institutions include the University of Wisconsin at Madison, MIT, the University of Florida, and the National Institute of Standards and Technology (NIST). The Micro-X payload will use a

121-pixel (11×11) X-ray calorimeter array with superconducting transition edge (TES) thermistors operating at 50 mK. It is designed to have an energy resolution of 2 eV (FWHM) across the energy band from 0.05 to 2 keV. The Micro-X payload will use a focusing optic designed and produced at Goddard for the SXS sounding rocket that flew in 1989 and is the predecessor of the optics used for BBXRT, ASCA, Astro-E2, and Astro-H.

The Micro-X payload is scheduled to fly in late 2015 to observe the bright eastern knot of the Puppis A supernova remnant. The detector array is designed and produced at Goddard and will be read out using a cryogenic SQUID multiplexer and room-temperature electronics jointly developed by Goddard and NIST. Goddard has already provided the refurbished SXS X-ray optic with 200-cm² collecting area at 1 keV and a 2.5 arcmin PSF.

Micro-X will provide some of the first detailed high-resolution spectra of a supernova remnant, with about 40,000 counts expected during the flight. The payload will be the first opportunity to utilize high spectral resolution broadband spatial-spectral imaging and will provide a glimpse of what we can expect from Astro-H and future larger-scale calorimeter instruments.

Off-Plane Gratings Rocket Experiment (OGRE)

OGRE is an APRA-funded rocket flight expected to launch from Wallops in 2017. Its primary objective is to demonstrate key technologies necessary for a future X-ray observatory and provide the highest spectral resolution of $E/\Delta E \sim 2000$ between 0.2–1.3 keV. It is a collaborative effort of the University of Iowa (PI, Randall McEntaffer) and Goddard. It will integrate two key technologies already developed in a laboratory setting that have not been flight-proven. OGRE will use a slumped glass Wolter telescope, to be made by GSFC's Next Generation X-ray Optics team led by Zhang, to provide excellent spatial resolution and increased throughput. A successful rocket flight will demonstrate its technical readiness, a requirement for flying this technology in future Explorer or major large X-ray missions. OGRE will also use radially grooved and blazed off-plane gratings to reduce grating aberrations and to focus the spectrum to one side of zero-order. Gratings of this type were invented in the 1980s and developed in the last decade but have not been flown. The spectrum will be focused onto a high spatial resolution CCD camera.

OGRE will produce the highest resolution spectrum of Capella to date. Capella is a binary system consisting of a G8 III giant and a G1 III giant. Strong coronal activity makes Capella one of the brightest X-ray sources in the sky. The emission-line-dominated spectrum often has been used as a calibration target and is included in the Chandra Emission line Project (<http://cxc.harvard.edu/elp/ELP.html>) with the goal of improving plasma spectral models with empirical line detections.

X-ray Quantum Calorimeter (XQC)

The X-ray Quantum Calorimeter (XQC) is a broadband non-dispersive X-ray spectrometer built to study the diffuse soft X-ray background (0.05–2 keV) from a sounding rocket. The instrument is designed to differentiate among the spectral components that make up the background, including emission from the Local Bubble, the our galaxy's halo, and solar wind charge exchange. The spectrometer utilizes a 36 pixel X-ray calorimeter array with 8 eV FWHM energy resolution that was designed and produced at GSFC. The project is led by the University of Wisconsin, Madison. ASD research team members include Meng Chiao, Megan Eckart, Richard Kelley, Caroline Kilbourne, Scott Porter, and graduate student Gabriele Betancourt-Martinez.

The most recent launch of XQC occurred on Nov. 3, 2013. Data analysis from the flight is ongoing, led by University of Wisconsin graduate students. The larger-than-expected (by an order of magnitude) launch vibrations due to a second-stage motor instability caused a significant detector temperature drift during observation and new analysis tools are required to correct the data. The final results are expected in 2015. The next launch of XQC has yet to be scheduled, but it will be part of the planned sounding rocket campaign in Woomera, Australia.

In parallel, members of the Goddard X-ray microcalorimeter group in the X-ray Astrophysics Lab and the Detector Systems Branch worked extensively with University of Wisconsin graduate student Kelsey Morgan on her NASA Space Technology Research Fellowship (NSTRF) project to develop a next-generation detector array for the XQC payload. The proposed large-area TES microcalorimeters will achieve ~2 eV FWHM energy resolution to enable measurements of the 0.25 keV diffuse X-ray background. This waveband is essential for studying the roles of solar wind charge exchange vs. thermal emission and the 8 eV FWHM resolution of the cur-



The XQC launch in November 2013

rent-generation XQC array is inadequate to resolve the majority of the emission lines in this crowded region. In 2014, Morgan completed the mask layout for the prototype TES microcalorimeters that are targeted to achieve 2 eV energy resolution with the required pixel area (~900 x 900 microns – more than ten times our standard TES microcalorimeter pixel size). Initial devices were fabricated in the Detector Development Laboratory and tested in the X-ray Astrophysics Lab. Several of these large-area device designs gave very promising results; modifications to the mask set were made based on these results and the second iteration of devices will be tested shortly.

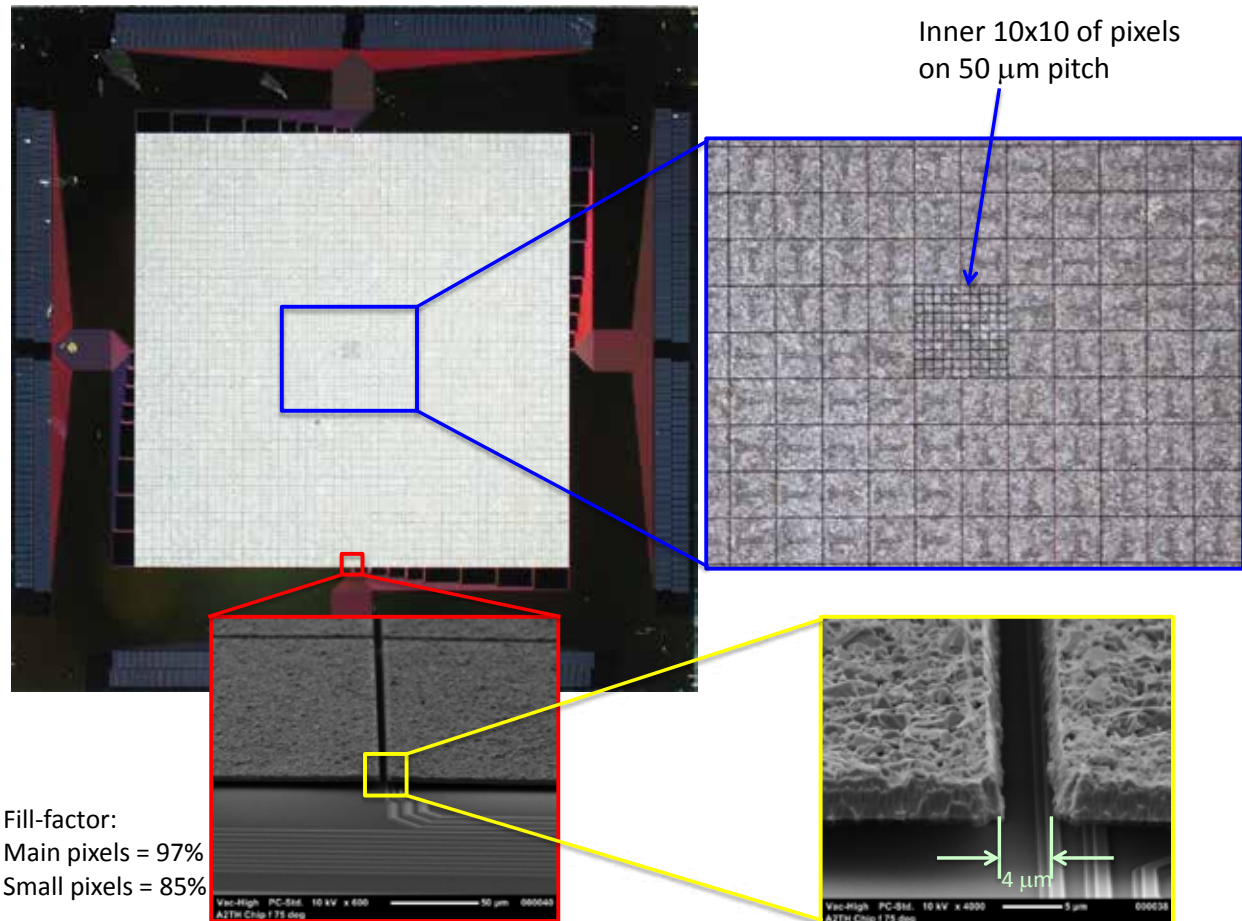
INSTRUMENTATION AND TECHNOLOGY DEVELOPMENT

X-ray Calorimeter Development

An X-ray microcalorimeter is used to determine the energy of an incident X-ray photon by measuring a small change in temperature with a highly sensitive thermometer. Arrays of these devices can be used to study various high-energy astrophysical objects using imaging spectroscopy.

Progress is continuing within the X-ray microcalorimeter group through the development of three generations of microcalorimeters. First, the group has recently delivered the focal plane array for the Soft X-Ray Spectrometer (SXS) instrument on ASTRO-H, a powerful new observatory being developed by the Japan Aerospace Exploration Agency (JAXA) that is scheduled to launch in 2016. The fo-

cal plane array will consist of 36 pixels where the sensors are ion-implanted silicon semiconducting thermistors. Second, the group has been invited to participate in the latest large European Space Agency (ESA) mission called Athena, scheduled for launch in 2028. The microcalorimeter array baseline for the X-ray Integral Field Unit (X-IFU) instrument on this mission uses superconducting transition-edge sensor (TES) microcalorimeter arrays that our group will develop in collaboration with the National Institute of Standards and Technology (NIST) and Stanford University. This will consist of around 4,000 pixels. Third, the group is developing new capabilities for a future potential mission called the X-ray Surveyor, to be considered within the next U.S. Astrophysics Decadal Survey as NASA's next large mission. This will require a focal plane array of around 100,000 pixels. Magnetically coupled calorimeters (MCC) and TES are the two



A three-tiered Hybrid array that contains three different types of pixels on a 19 x 19 mm chip. Central region: 10 x 10 point source array. Single pixels on a 50 μm pitch. Absorbers: 46 x 46 μm . Second tier: 16 x 16 array of single pixels on a 250 μm pitch. Absorbers: 246 x 246 μm . Third tier: 24 x 24 of 2 x 2 hydras, absorbers on the same 250 μm pitch. The second and third tiers are indistinguishable in the photograph. Absorbers are a bismuth (3 μm)-gold (1.5 μm) bilayer, with bismuth on top.

prime microcalorimeter technology options for this mission now being developed.

The group is currently researching a number of different approaches to allow increased array size. This includes the development of position sensitive calorimeters, in which a single sensor is attached to a number of different absorbers (known as a “hydra”) with slightly varying thermal conductances. The absorber of the X-ray can be determined from measuring the signal pulse rise-time, which allows discrimination between the different pixels. The GSFC group has recently demonstrated a hydra in which a single TES was attached to 9 different absorbers, and achieved an energy resolution across the 9 pixels of 2.4 eV at 6 keV. The group is also focusing on two types of multiplexing techniques to increase the number of TESs or MCCs that can be read out from a single amplifier channel. In this past year it has been demonstrated that a single multiplexer can read out 32 different pixels with a resolution of 2.3 eV at 1.5 keV and 3.3 eV at 6 keV, which is very close to fulfilling the requirements of the Athena X-IFU instrument. In a separate effort, we are beginning to develop the ability to read out TESs or MCCs using a microwave multiplexing technique, in which a series of sensors are coupled to narrow bandwidth resonators that include a non-hysteretic superconducting quantum interference device (SQUID). With this approach, the potential exists for around a thousand sensors to be read out through a single read-out chain, requiring just two coaxial cables.

Goddard Space Flight Center is the only institution playing a leading role in the development of the three dominant X-ray microcalorimeter technologies. The scientists of the ASD microcalorimeter development team include Joe Adams, Simon Bandler, Meng Chiao, Megan Eckart, Fred Finkbeiner, Richard Kelley, Caroline Kilbourne, Scott Porter, and Steve Smith, along with post-doctoral associates Heather Audley, Sang-Jun Lee, and Wonsik Yoon and graduate student Gabriel Betancourt-Martinez. Progress is made possible through a strong collaboration with James Chervenak, John Sadleir, and Edward Wassell of Goddard’s Detector Systems Branch.

Laboratory Astrophysics Using an X-ray Microcalorimeter with an Electron Beam Ion Trap

Our laboratory astrophysics program is designed to simulate astrophysical plasmas in the laboratory in order to benchmark and provide guidance to the atomic codes that form the basis of the spectral

synthesis models used in X-ray astrophysics. These models are used to relate spectra observed from an astrophysical object to conditions in the source, including temperature, ionization equilibrium, composition, density, turbulence and bulk motion. This work is fundamentally important as high-resolution spectroscopy becomes the dominant tool in exploring the physics of X-ray-emitting objects.

This has already started with the observation of bright point sources with the high-resolution dispersive spectrometers on Chandra and XMM-Newton. It will become critically important with the upcoming Astro-H and X-ray missions that follow, including Athena. Our program is designed to validate and correct the accuracy of the spectral synthesis models in controlled ground-based experiments, giving us confidence that we have correctly ascribed observed spectral features to known conditions in the astrophysical source.

The basis of our program is a high-resolution non-dispersive X-ray calorimeter spectrometer, a suite of very-high-resolution dispersive spectrometers, and the Electron Beam Ion Trap (EBIT) plasma generator at the Lawrence Livermore National Laboratory (LLNL). ASD scientists include Porter, Kelley, Kilbourne, Adams, Smith, Leutenegger, and Betancourt-Martinez. Other collaborating institutions include Stanford University and NIST. The LLNL EBIT can produce nearly any plasma conditions, from low-charge states in light elements to bare uranium, with electron beam energies of up to 200 keV. Nearly any charge state of any astrophysically interesting element can be produced, either as a pure charge state or in a Maxwellian distribution at known temperature.

Non-equilibrium ionization conditions can also be produced with almost any astrophysically interesting ionization parameter. Typical measurements in our program include spectral-line identification, absolute cross sections, recombination, charge-exchange recombination, and cross sections in thermal and non-thermal distributions. Measurements are related back to theory, the results of atomic calculations, and to the standard X-ray spectral synthesis models used in X-ray astrophysics.

A key instrument in these measurements is a broadband high-resolution X-ray calorimeter instrument provided by Goddard beginning in 2000 and now on its third revision. This system has been operated almost continuously for the past 15 years. It has produced well over 40 peer-reviewed articles, and it has made critical measurements of absolute cross sections in L-shell iron and nickel, as well as charge exchange measurements in sulfur, carbon,

oxygen and iron. Many investigations are ongoing. Recent emphasis has been a detailed look at L-shell charge exchange, mostly with sulfur and iron, as a function of ionization state, a key component of magnetospheric charge exchange for which there exists no predictive theory. Magnetospheric and heliospheric charge exchange are key components of spatially, spectrally, and temporally variable foreground emission which complicate observations of, for example, the soft X-ray background, warm-hot intergalactic medium, and clusters of galaxies. Charge exchange emission is also very diagnostic and if observed in a celestial source can provide key information on the composition, ionization state, and relative velocity of both the donor and acceptor species. Our laboratory investigation is unique in the world at providing the first controlled high-resolution spectra of charge exchange in astrophysical elements and is geared to provide information to guide the development of a predictive atomic theory, especially for the key L-shell emission which dominates local charge exchange.

Goddard first installed an X-ray calorimeter at the LLNL EBIT facility in the summer of 2000; the XRS/EBIT was based on the engineering-model detector system for the Astro-E observatory. The system was significantly upgraded using technology developed for Suzaku (Astro-E2) in 2003. A dedicated facility-class instrument designed for laboratory astrophysics from the ground up was installed in 2007. The current instrument, dubbed the EBIT Calorimeter Spectrometer (ECS), utilizes a 32-channel X-ray calorimeter array from the Astro-E2 program installed in a long-lifetime automated laboratory cryostat that enables continuous experiments for up to 70 hours, with a two-hour recharge. The detector array is populated with 16 mid-band (0.05–12 keV) X-ray absorbers with 4.5 eV FWHM resolution at 6 keV, and 16 high-band (0.1–100 keV) X-ray absorbers with 30 eV FWHM at 60 keV.

In addition to operating the ECS, we recently (spring 2011 and spring 2012) refurbished the XRS/EBIT spectrometer to perform photoexcitation measurements at the SLAC Linac Coherent Light Source (LCLS). In this experiment we combined a portable EBIT, the XRS/EBIT spectrometer, and a monochromator with the LCLS light source to breed and observe X-ray emission from photoexcitation in highly charged ions.

We are currently designing and constructing the fourth-generation instrument that will be based on detector technology from the Athena development program. It will be installed in a completely automated cryogen-free cryostat. This fourth-gen-

eration instrument is dubbed the Transition-Edge Microcalorimeter Spectrometer (TEMS) and will be composed of an array of 256 mid-band (0.05–10 keV) pixels with 2.0 eV resolution at 6 keV. The TEMS instrument will become the workhorse in our laboratory astrophysics program to ensure that our measurements and understanding of atomic processes are ready to interpret the spectra we will obtain with Astro-H and future observatories. TEMS will be installed at the EBIT facility in late 2015.

Next Generation X-ray Optics

The group, led by Zhang, has demonstrated the construction of mirror modules that perform at 10 arcsecond levels and pass all necessary environmental tests, including vibration, acoustic, and thermal vacuum. They have continued their effort to improve the angular resolution, with a plan to demonstrate 5 arcsecond resolution by the end of 2015 and paving the way for achieving 1 arcsecond resolution by the end of this decade. The construction of a mirror module is a three step process: substrate fabrication, coating, and alignment and bonding. Each step is improved in parallel.

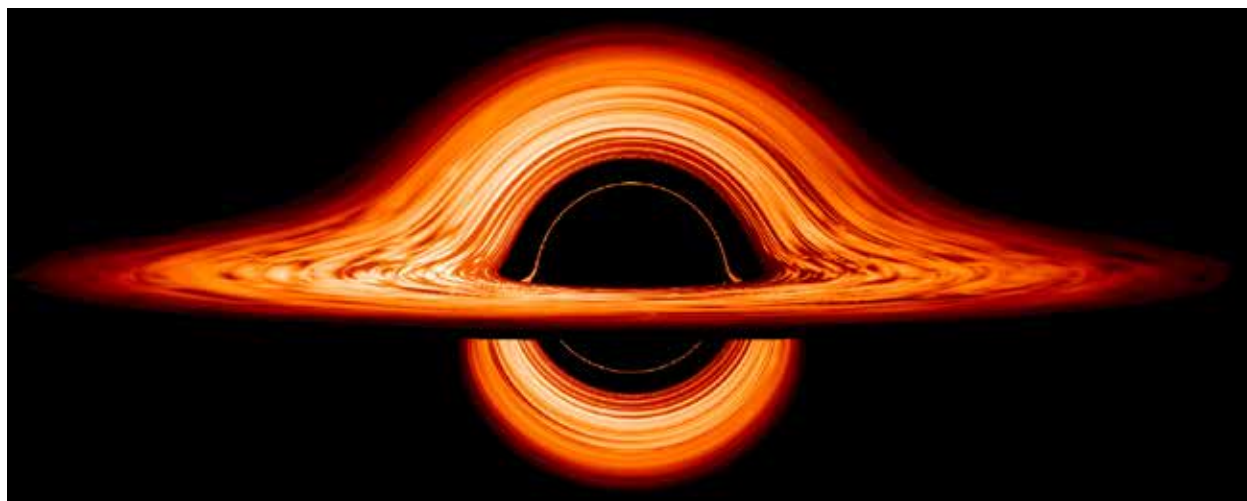
For substrate fabrication, they are transitioning from slumping thin glass sheets to polishing and slicing single crystal silicon. This novel approach of making mirror substrates by polishing and light-weighting single-crystal silicon mirrors has the potential of making diffraction-limited X-ray mirrors.

Over the last year, they continued the process of optimizing the coating and annealing process to minimize figure distortion caused by thin film stress. By 2015 they expect to be able to reduce the contribution of coating distortion to angular resolution to less than 1 arcsecond.

The group continues to verify and perfect the entire process by constructing mirror modules that contain three co-aligned pairs of Wolter I mirrors. The complete end-to-end construction and testing process allow researchers to identify and address problems that may otherwise elude them during individual steps. They are well on their way toward making 5 arcsecond modules by the end of 2015, enabling several potential Explorer missions.

Athena Mission Studies

In late 2013, ESA announced that its L2 mission (launch in 2028) would be an X-ray observatory that addressed the theme “The Hot and Energetic Universe.” The mission concept Athena was se-



This simulated view of a black hole and its accretion disk appeared on the cover of the PRAXyS proposal and shows the lensing effects of extreme gravity. In this edge-on view, light from the far side of the disk is distorted into arcs above and below the black hole. The disk material is moving near the speed of light, which results in a strong Doppler shifts and makes the left side—moving toward the observer—significantly brighter than the right side, which is receding. Credit: Jeremy Schnittman

lected by ESA in mid-2014 as L2, in response to an ESA Announcement of Opportunity. NASA has expressed an interest in participating in Athena by providing mission-enhancing hardware contributions. NASA also plans to participate in the Science Ground System and fund a U.S. Guest Observer program.

In fall 2014, ESA formed a Science Study Team to develop the Athena Science requirements and advise ESA during the study phase. Randall Smith (SAO) was appointed as the NASA representative; Petre, as NASA Study Scientist, is an *ex officio* member.

Three NASA hardware contributions are being explored: contributions to the two focal plane instruments, the Wide Field Imager (WFI) and X-ray Integral Field Unit (X-IFU), and to the X-ray mirror. A GSFC/NIST/Stanford team led by Richard Kelley has negotiated a role in the X-IFU. ESA has expressed interest in NASA providing a part of the mirror, and is particularly interested in the slumped glass optics developed by ASD's Will Zhang. No formal commitment to either has been made, but accommodation and technology development studies have commenced and will continue through 2015.

X-RAY POLARIMETRY

Proposed Mission

The X-ray polarimetry group led the development and submission of a Small Explorer proposal: the Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS), submitted in December

2014 in response to NASA HQ Announcement of Opportunity NNH14ZDAO130. PRAXyS will be the first X-ray observatory dedicated to measuring the X-ray polarization from a variety of black holes and neutron star sources. Polarization provides insight into the geometry of compact objects that will be unavailable from imaging observations until sub-microarcsecond resolution is available. The cover of the PRAXyS proposal shows a remarkable simulated image of a black hole accretion disk. The structure above and below the disk arises from emission behind the black hole which is gravitationally bent into a distant observers' line of sight. This bending distorts the polarization properties of the direct emission and is most pronounced for radiation which starts closest to the inner edge of the disk. As the inner disk is expected to be hottest, energy dependent polarization effects are expected and carry information about the properties of both the black hole and the accretion disk. For neutron stars, which can be observed at a variety of angles, the intense magnetic fields act as polarizers; phase dependent polarization will reveal details about the strength of the magnetic fields and locate the emission, which may come from the neutron star surface or within the magnetic atmosphere.

The GSFC X-ray Laboratory contributions to PRAXyS include Scientific Leadership (PI Jahoda, Project Scientist Kallman), key payload components including polarimeters (Hill-Kittle, Black) and mirrors (Takahashi, Soong), and science operations, algorithms, and archiving (Markwardt, Strohmayer, and Angellini). The design life of two years accom-

modates a 10-month primary mission with the possibility of a community-driven Guest Observer phase. The payload and mission design draw heavily from the technically successful PDR held in 2012 for the Gravity and Extreme Magnetism Small Explorer (GEMS).

Laboratory Work

Characterization of an engineering unit detector for the GEMS mission using the Brookhaven National Laboratory's synchrotron light source in 2013, revealed a position-dependent response. The cause of this position dependence is now understood to be asymmetric diffusion in the transfer gap between the multiplication stage and the readout, and can therefore be calibrated. However, laboratory efforts have been directed first to reducing the magnitude of the position dependence, which has had the additional positive effect of reducing the number of parameters needed for calibration (perhaps to just a one parameter characterization of transfer gap diffusion).

Production of a narrow gap design which reduces the transfer gap to about 250 microns (from

about 800) necessitated a new assembly method based on adhesive rather than clamped mounting. Performance tests have confirmed the expected performance (reduced position dependence, simpler calibration) while engineering tests have demonstrated that the narrow gap is robust against vibration and temperature swings. The combined demonstrations brought the narrow gap design to TRL-6, and this design is incorporated into the baseline detectors proposed for the PRAXyS Small Explorer. The adhesive mountings also allow investigation of alternative technologies for the Gas Electron Multiplier (GEM). We have begun investigations of replacing GEMs (typically metalized and patterned insulators) with pairs of fine-pitch mesh under tension. These insulator-free multipliers show promise of higher gain and simplified operation for concepts based on negative ion (rather than electron) drift. Negative ion drift polarimeters will open the possibility of negligible diffusion and long drift lengths which enables, among other things, wide field of view detectors suitable for observing unpredictable transients such as gamma-ray bursts.

Gravitational Astrophysics Laboratory



Dr. Robin T. Stebbins
Lab Chief

Laboratory Overview

The Gravitational Astrophysics Laboratory (Code 663) conducts a broad range of scientific investigations into astrophysical regimes dominated by extreme gravity. The laboratory provides the scientific and technical leadership to develop space-based gravitational-wave observatories and includes a mix of theorists and experimentalists. Research encompasses a variety of areas, including theoretical high-energy astrophysics, numerical relativity, and the study of sources, data analysis, mission formulation, and precision metrology for a gravitational wave observatory. In addition to the civil servant staff, the laboratory has eight university scientists, two NASA postdoctoral fellows, two engineers and two graduate students.

Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
John Baker	Gravitational wave astrophysics, numerical relativity, data analysis, GRMHD, microlensing	WFIRST-AFTA eLISA	WFIRST Study Scientist <i>JSI</i> eLISA Consortium
Jordan Camp	Multiwavelength astronomy, precision measurement	LIGO, eLISA, ISS-Lobster	<i>LSC</i> eLISA Consortium
Alice Harding	Pulsars, gamma-ray emission	Fermi, NICER	Fermi Science Team, <i>JSI</i>
Demos Kazanas	Black holes, compact objects, active galactic nuclei, gravitation		
Jeff Livas	Gravitational wave astrophysics, precision measurement, laser communications, small satellites	eLISA, LISA Pathfinder, CubeSats/Small Sats	eLISA Consortium
Jeremy Schnittman	Black holes, X-ray polarization, gravitational wave astrophysics, exoplanet atmospheres	eLISA, PRAXyS, ISS-Lobster, ATLAST	<i>JSI</i> <i>Johns Hopkins University</i>
Robin Stebbins	Gravitational wave astrophysics, precision measurement	eLISA GRACE Follow-On	eLISA Consortium
Floyd Stecker	Cosmic gamma rays, gamma-ray astronomy, high-energy astrophysics, astrophysical tests of relativity, dark matter	Fermi	<i>UCLA</i>
J. Ira Thorpe	Gravitational wave astrophysics, precision measurement	eLISA, LISA Pathfinder, GRACE Follow-On	LPF Science Working Team, eLISA Consortium
Richard Fahey	Relativity	Emeritus	<i>U.S. Naval Academy</i>
Vigdor Teplitz	Relativity, exotic particles	Emeritus	<i>U.S. Department of State</i>

SCIENCE HIGHLIGHTS

Fermi Uncovers Black Widow Pulsars

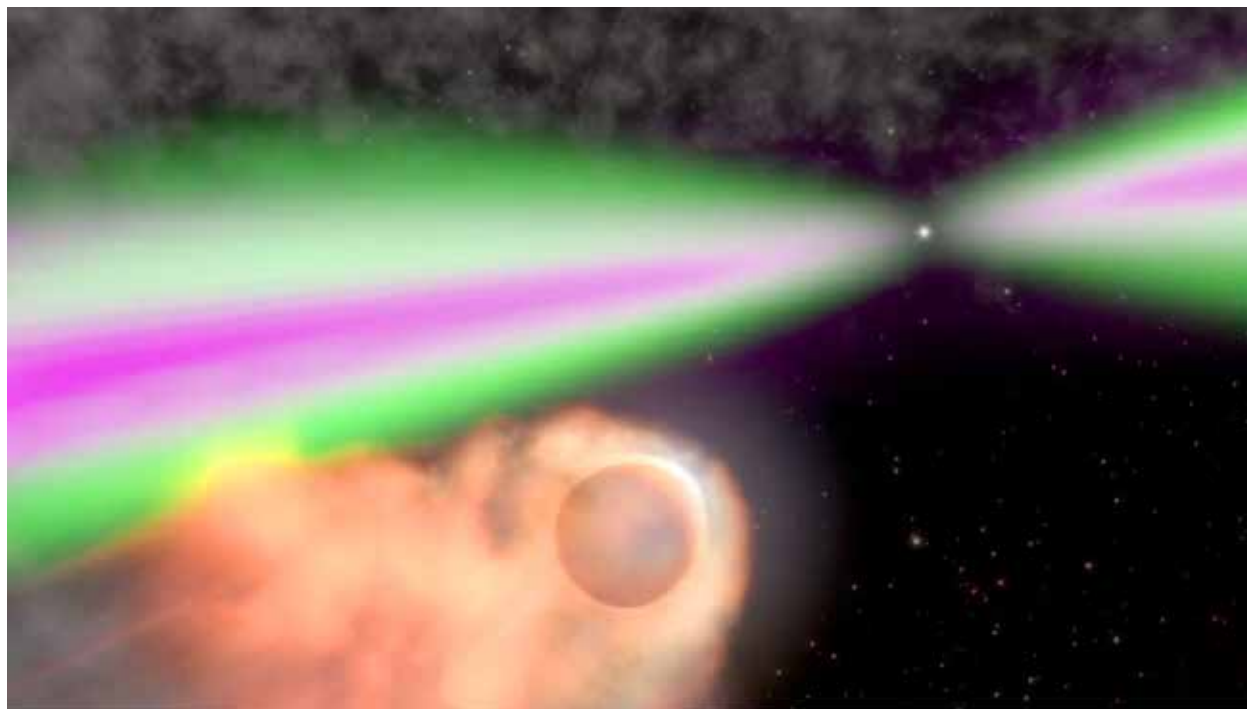
During its first year of operation, the Fermi Gamma-ray Space Telescope began detecting hundreds of sources, many of which could not be identified with known sources at any other wavelengths. Over the next few years, radio searches at the positions of a subset of these unidentified sources yielded a surprisingly large number (63 to date) of new millisecond pulsars, neutron stars rotating near their break-up rate at hundreds of times a second. Although Fermi is able to find new pulsars by their gamma-ray pulsations alone, most of these new radio millisecond pulsars are in binary systems where their orbital motion makes gamma-ray pulsation searches impossible. But by using the radio timing as a guide, Fermi was able to detect the gamma-ray pulsations as well.

A handful of bright unidentified sources eluded this approach, leading Roger Romani of Stanford University to try searching with optical telescopes. One source showed optical variations with a period of 93 minutes, and he deduced that this was possibly the companion to a millisecond pulsar. Using the optical orbital parameters, the Fermi team em-

barked on a blind search for gamma-ray pulsations using the massively parallel processor at Hannover, Germany, and an algorithm based on those used for gravitational wave searches. The gamma-ray pulsations were found, finally identifying this source as a 2.5 ms pulsar, designated PSR J1311–3430, with a companion of only 12 to 17 Jupiter masses.

With its extremely small companion mass, this pulsar joined an exclusive club known as black widow pulsars. These are energetic, rotation-powered pulsars that are evaporating their companion stars by intense surface heating and ablation. The tiny stars are heated to tens of thousands of degrees C on the sides facing the pulsars in these tight, tidally-locked systems. This uneven heating produces the observed optical modulation, as the heated and unheated sides alternately come in and out of view. With the high rate of mass loss, the companions will eventually disappear, leaving an isolated pulsar.

Long radio searches at the Green Bank Telescope finally detected radio pulsations from PSR J1311–3430, but only intermittently. The slow destruction of the companion star fills the system with ionized gas, creating a thick veil that hides the radio pulses most of the time, allowing only occasional glimpses of the pulsar. It is therefore very unlikely that this system would have been discovered without the use of gamma rays that are not blocked by the gas.



A black widow pulsar (background) emits pulses of gamma rays and a powerful wind. Orbiting at a distance comparable to that between Earth and the sun, the pulsar is intensely heating and ablating its tiny stellar companion. Credit: NASA's Goddard Space Flight Center

Although the companion of PSR J1311–3430 is an extreme lightweight, the pulsar is an extreme heavyweight for a neutron star. Weighing in at possibly 2 solar masses from pulsar timing measurements, it is near the upper limit of mass allowed by neutron star equations of state.

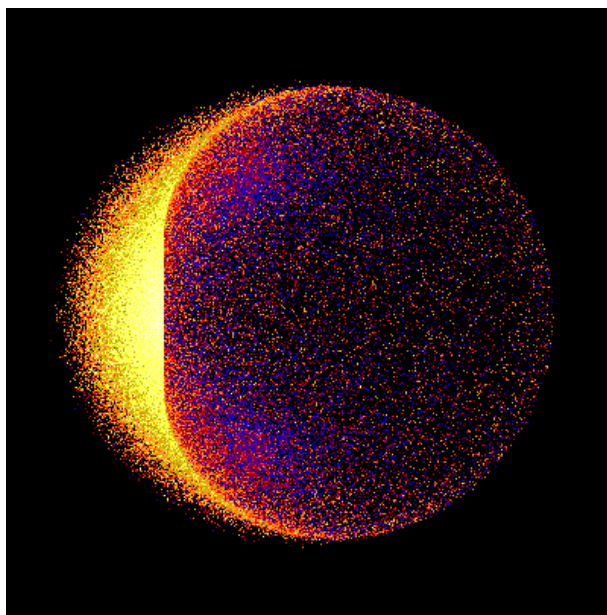
Fourteen more new black widow systems have been discovered through radio searches in Fermi sources, and another one like PSR J1311–3430 through gamma-ray pulsations using an optically detected orbit. Seven new redback systems, cousins and possibly precursors of black widows with heavier companions, have also been found in Fermi sources. There are undoubtedly many more of these systems out there to be discovered.

Black Holes, Dark Matter, and Bright Light

The decade starting from the mid-1960s was a time of tremendous theoretical progress in the understanding of black holes, beginning with the derivation of the Kerr metric in 1963 and culminating with the discovery of Bekenstein-Hawking radiation in 1974. Kip Thorne describes this time as the Golden Age, and it also coincided with key astronomical discoveries including the first convincing detection of a stellar-mass black hole, Cygnus X-1, in 1971. Yet for the most part, the Golden Age theoretical predictions have yet to be tested with observations.

One particularly interesting prediction regarding spinning black holes was made by Roger Penrose in 1969. He showed that a particle orbiting within the ergosphere—a region just outside the event horizon, where the extreme warping of space-time forces all particles to orbit in the same direction—could in principle decay into two daughter particles, one of which gets captured by the black hole while the other escapes. The remarkable feature of the ergosphere is that any particle that tries to “swim upstream” against the rotational direction of the black hole will have a negative energy. Thus, to conserve total energy, the other particle can escape with more energy than the parent particle, thereby extracting energy from the black hole.

However, it was soon shown that even in the most favorable conditions, this energy extraction method (today called the Penrose process) could only ever achieve very modest efficiencies, on the order of 20 percent, i.e., the emerging particle has 20 percent more energy than the original. In 1977, Piran and Shaham explored the collisional Penrose process, in which two particles collide in the ergosphere, either scattering or annihilating into photons. While



Simulated image of high-energy photons produced by annihilating dark matter just outside a spinning black hole. The observer is located at a large distance from the black hole, in the equatorial plane, with the spin axis of the black hole pointing up. The highest-energy photons, corresponding to the collisional Penrose processes discussed here, emerge from the bright yellow region to the left of center.

this process does allow for very high energies in the center-of-mass frame, by the time the daughter photons reach an observer at infinity they are so highly redshifted that the net efficiency is only marginally higher (now ~30 percent) than the original process.

Despite the fact that the Penrose process has never been directly observed, there has been significant renewed interest in this subject following a 2009 paper by Banados, Silk, and West. There they focused on how extremely energetic collisions could occur between particles in the ergosphere and how they might provide a new window into high-energy particle physics. This motivated Jeremy Schnittman in ASD’s Gravitational Astrophysics Laboratory to carry out a numerical calculation to determine the full three-dimensional distribution of dark matter particles around a spinning black hole. Whenever two of these particles collide, they produce two gamma rays, which then either get captured by the black hole or escape to a distant observer.

When considering the problem in its full generality (the analytic approach of previous work necessarily limited it only to special cases), Schnittman found a population of much more energetic photons that are still able to escape the black hole. In a paper published in *Physical Review Letters*, he showed that

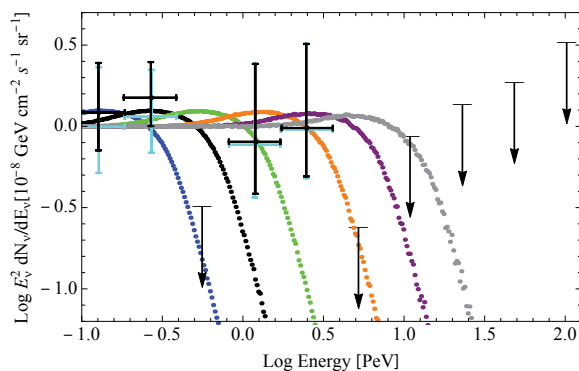
the new upper limit for energy extraction is greater than 500 percent of the initial rest mass energy. One way to potentially observe this feature would be to measure a high-energy cutoff in the gamma-ray annihilation spectrum coming from an otherwise quiescent black hole. Schnittman and collaborators are now analyzing data from the Fermi gamma-ray observatory to search for such a signal, or set upper limits on the dark matter annihilation cross section.

Superluminal Neutrinos

The possible existence of superluminal neutrinos was brought to the attention of the physics community, as well as the news media, by their apparent production in the Large Hadron Collider. This claim was later retracted. However, the possibility of slightly superluminal neutrinos as a consequence of quantum gravity theories has been of significant fundamental interest.

Putative superluminal neutrinos would lose energy by the emission of electron-positron pairs in a vacuum. Floyd Stecker and Sean Scully, writing in the journal *Physical Review D*, have shown that if this process takes place over cosmological distances, it would lead to a predicted cutoff in the spectrum of high-energy astrophysical neutrinos. They point out that such a cutoff may have been seen by the IceCube neutrino detector at the South Pole.

This cutoff is indicated in the graph, which compares IceCube data with upper limits on the high-energy astrophysical neutrino flux, by the orange curve. A cutoff at this energy could be caused by neutrinos having a velocity greater than the speed of



Calculated neutrino spectra with vacuum pair emission and redshifting compared with the IceCube data, both including a subtraction of atmospheric charm neutrinos at the 90 percent confidence level (cyan) and omitting such a subtraction (black). Curves from left to right are spectra obtained with rest-frame threshold energies of 1, 2, 4, 10, 20, and 40 PeV.

light by a factor of $(0.5 \text{ to } 1.0) \times 10^{-20}$. If the observed spectral cutoff is not caused by this effect, their result corresponds to the most stringent upper limit on superluminal neutrino velocities yet obtained.

PROJECTS IN DEVELOPMENT

ASCENDS

The laser technology developed for LISA is being applied to laser remote sensing for Earth and planetary sciences. To predict long-term changes in the climate cycle, NASA is planning the Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) mission. This mission will measure the global distribution of carbon dioxide (CO₂) mixing ratios from an Earth-orbiting satellite. It has set unprecedented targets for precision that require much better laser frequency precision than most telecom applications.

A candidate lidar for ASCENDS being developed at Goddard uses a nadir-viewing, integrated-path differential-absorption lidar technique to scan a single atmospheric CO₂ absorption line at 1572 nm, a telecom wavelength. The laser frequency fluctuation causes a variation in measured CO₂ transmittance, resulting in an uncertainty in the column number density estimation. The error caused by the frequency uncertainty needs to be a small fraction of the measurement error budget.

To achieve this goal, Numata has applied absolute and offset phase-locking techniques, both being based on similar principles to be used in LISA. To enable fast phase-locked wavelength switching,



Seed laser rack for ASCENDS flight campaign

a widely-tunable monolithic semiconductor diode laser was adopted as a seed laser. The demonstrated tuning range, switching time, and frequency stability satisfied the ASCENDS's requirements. The system is now adopted as the baseline design of the seed laser for ASCENDS. The system was successfully tested in an ASCENDS's airborne campaign in the summer of 2014.

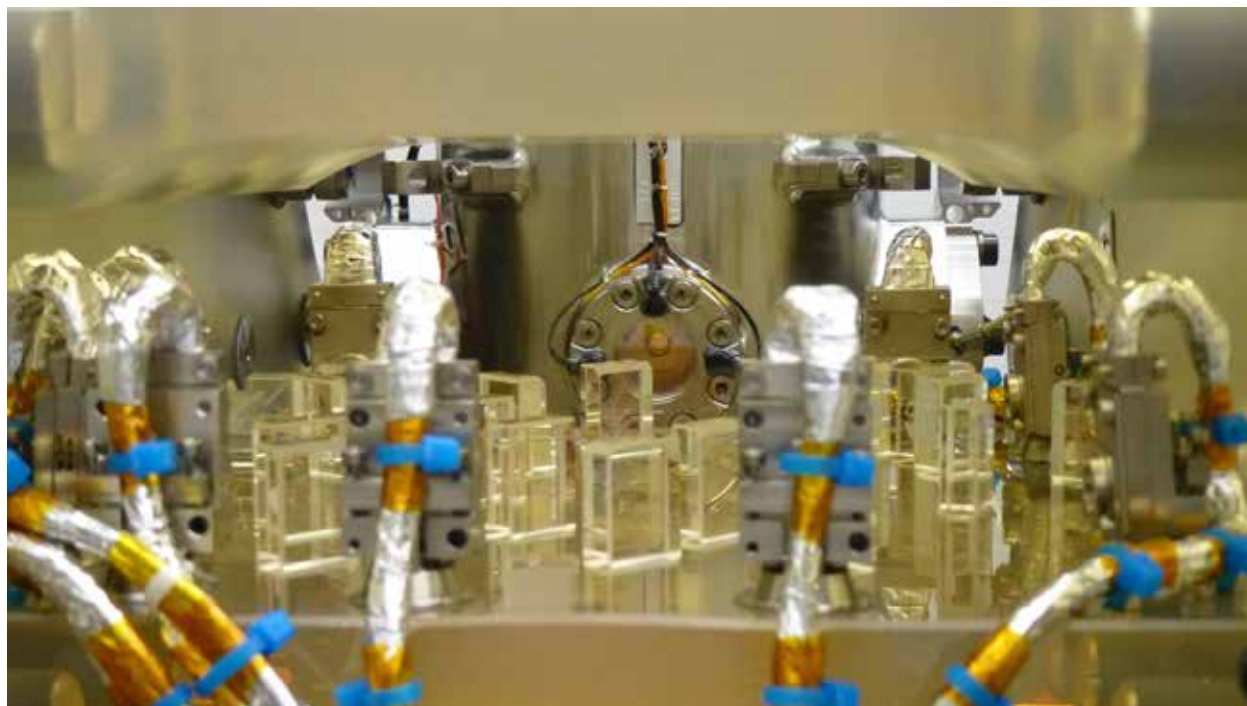
The 1064 nm external cavity laser (PW-ECL) developed for LISA is also playing an important role in measuring the second most important greenhouse gas, methane, at 1651 nm. The earth methane lidar under development at Goddard uses a 1651 nm optical parametric oscillator (OPO) pumped by a 1064 nm laser. The 1064 nm pump laser must have a narrow output linewidth and high stability. Therefore, the 1064 nm PW-ECL was adopted as a seed laser because of its compactness, low cost and high stability. The OPO system will be tested in an airborne campaign in the summer of 2015.

LISA Pathfinder

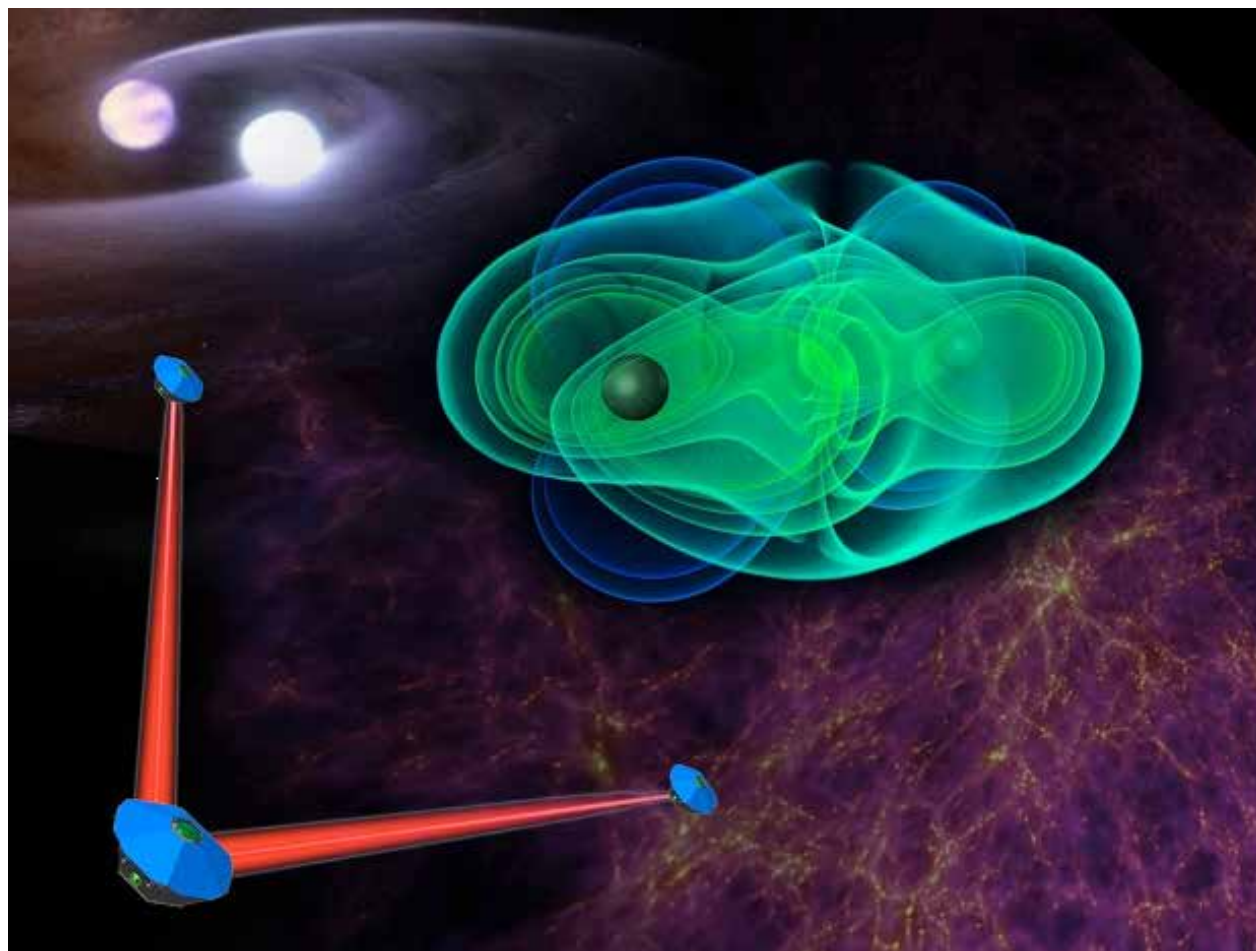
Due to launch in fall 2015, LISA Pathfinder (LPF) is a technology demonstrator mission targeting several key aspects of the detection and measurement of gravitational waves using large laser interferom-

eters in space. This will pave the way for a future gravitational wave observatory such as the Laser Interferometer Space Antenna (LISA) that will study astrophysical phenomena such as the collision and merger of supermassive black holes in the distant universe, the capture of compact objects by massive black holes in our local universe, and large populations of compact objects in binaries in our own galaxy.

The primary purpose of LPF is to demonstrate the technique of *drag-free control* for realizing an inertial test particle. Isolating a reference mass from all non-gravitational forces is a key challenge for the designers of gravitational-wave detectors and is a problem that ultimately limits the sensitivity of ground-based detectors such as LIGO at low signal frequencies (long wavelengths). In space, this isolation can be achieved by allowing the test mass to freely fall within a cavity inside the spacecraft. A control system monitors the position of the spacecraft relative to the test mass and maintains separation by applying small forces to the spacecraft using a microthruster system. The performance of a drag-free system is typically characterized by accelerations away from an ideal inertial test particle. For LPF, the requirement is that the deviations are less than 10^{-16} g over a twenty-minute interval.



The LISA Technology Package during the late stages of integration. Visible in the foreground is an ultra-stable optical bench that will be used to measure the relative position of the two gold-platinum test masses with a precision of a few picometers. The surface of one of the test masses is just visible inside the vacuum window in the background. Credit: ESA/Airbus Defense & Space Systems/CGS/U. Glasgow



Artist's concept of eLISA

LPF is managed by the European Space Agency and consists of two science payloads: the LISA Technology Package (LTP), provided by a consortium of European industry and universities, and the Disturbance Reduction System (ST7-DRS), provided by NASA with JPL as the lead center. LPF is currently in the final stages of integration, with the ST7-DRS payload already delivered and integration with the LTP expected in April 2015.

Gravitational Astrophysics Laboratory staff scientist Ira Thorpe is a member of the LPF Science Working Team and, together with postdoctoral researcher Jake Slutsky, is participating in preparations for LPF operations and data analysis. During 2014, both were active in the development of data analysis pipelines for several LTP experiments and participated in three science operations exercises in which simulated mission data was produced and analyzed in real-time at the mission science operations center and auxiliary facilities.

MISSION AND INSTRUMENT CONCEPTS

Evolved LISA (eLISA)

For more than two decades, NASA and the European Space Agency (ESA) have jointly studied a mission to put a gravitational wave observatory in space, called the Laser Interferometer Space Antenna (LISA). The concept has been highly ranked in the last two decadal reviews of astrophysics. In November 2013, ESA selected the science theme, the “Gravitational Universe,” for its third large-mission opportunity, known as L3, under its Cosmic Vision Programme. The planned launch date is 2034. ESA has invited a 20 percent participation by an international partner, and NASA’s Astrophysics Division has indicated an interest in participating.

For L3, the European community proposed a notional mission concept, called evolved LISA (eLISA), having two measurement arms, derived from

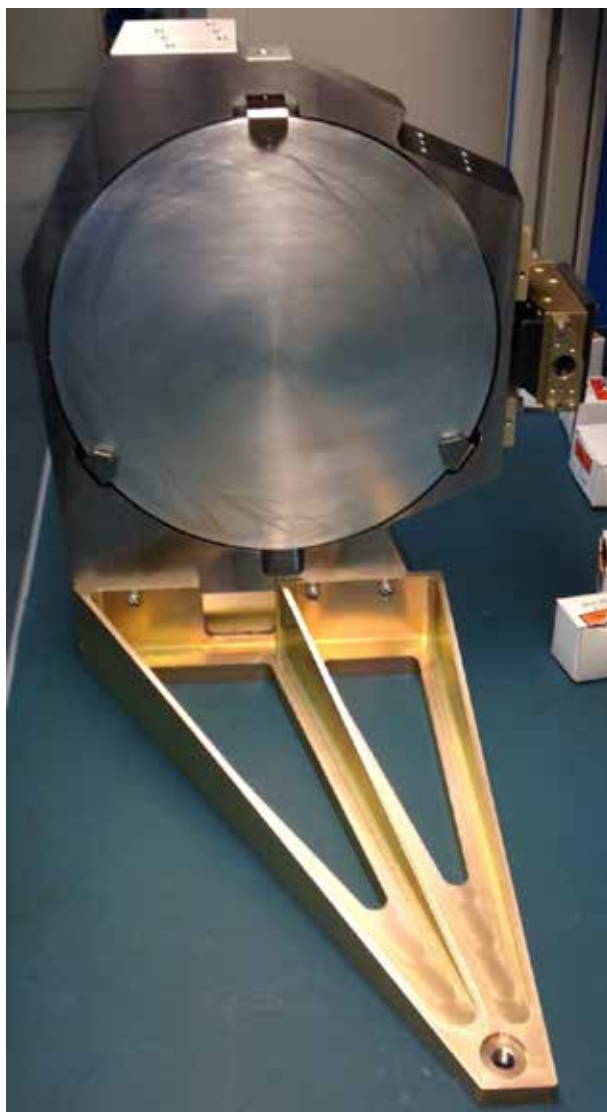
the well-studied LISA concept. In October 2014, ESA initiated a study of mission options by the Gravitational Observatory Advisory Team (GOAT), consisting of European, U.S. and Japanese researchers. Robin Stebbins is the NASA Observer on the GOAT and coordinates participation by three other U.S. researchers. The GOAT is analyzing many aspects of a gravitational wave mission and is expected to issue its report in early 2016. GOAT activities can be followed at its web site (<http://www.cosmos.esa.int/web/GOAT>).

The European gravitational wave community is organized as the eLISA Consortium (<https://www.elisascience.org>). The U.S. community, in particular scientists from the Gravitational Astrophysics Lab, has frequent interactions with the consortium. Some of those interactions are described in the subsections about LISA Pathfinder and technology development for a gravitational wave observatory.

Technology Development for Gravitational Wave Missions

The technologists of Gravitational Astrophysics Laboratory continued to study key and enabling technologies for space-based gravitational wave detection in 2014. In addition to developing technologies for a future U.S.-led gravitational wave mission, branch technologists are studying potential contributions to ESA's eLISA mission concept. These efforts were led by branch scientists Camp, Livas, Numata, Stebbins, and Thorpe with help from both contract and civil servant engineers. The technology-development efforts also provided educational opportunities for several students, including high school student Hudson Loughlin, undergraduates Robby Buttles, Michael Perlin, and Stephanie Chung, and graduate student Ryan Stein. Results from 2014's technology development work were presented at several conferences, including the 13th International Conference on Topics in Astroparticle and Underground Physics, the 225th American Astronomical Society Meeting, the 14th Meeting of the High Energy Astrophysics Division (HEAD), and the 2013 APS April Meeting.

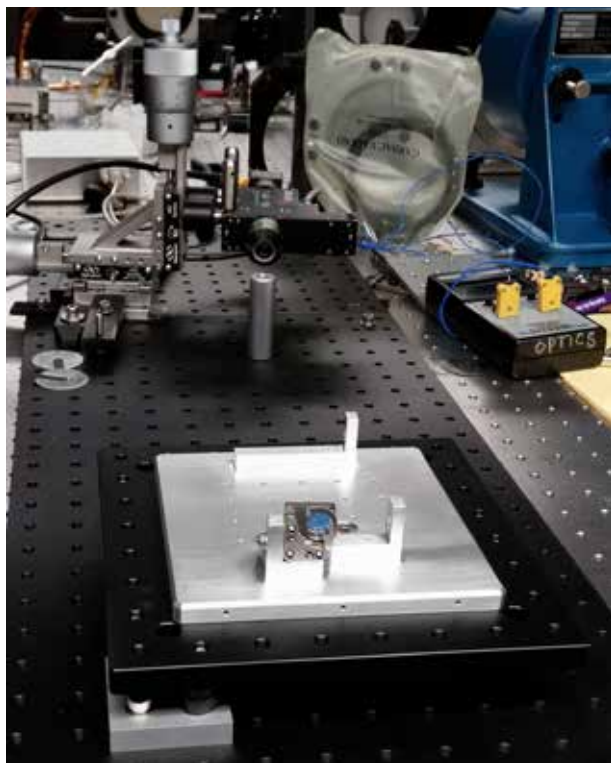
The immediate milestone for the program is the successful completion of the LISA Pathfinder Mission (LPF), expected to launch in 2015. Thorpe, the U.S. LPF science team representative, along with Slutsky, are supporting science mission operations simulations for the validation of the gravitational inertial sensor noise model and developing a proposal for an extended mission.



Prototype telescope under construction, looking into the primary mirror reference blank. The metering structure and secondary mirror mount will be added next.

Numata and Camp are pursuing the development of a candidate for the eLISA laser through an SAT award. This includes a 2W Yb fiber amplifier, and a planar-waveguide external cavity diode laser (PW-ECL) as a possible alternative to the traditional NPRO through the SBIR program with Redfern Integrated Optics in California. Work in 2014 includes building a low-noise fiber amplifier, reducing the 1064 nm ECL phase noise, and implementing an internal phase modulator on the ECL. The ECL will be included with the Yb pre- and power-amplifier as an all-waveguide-based laser system, and tested for TRL 5 in FY16.

Livas, together with postdoctoral fellow Shannon Sankar (USRA) and collaborators Peter Blake, Joe



Scattered light test bed to allow rapid measurement and reconfiguration of the tertiary (M3) and quaternary (M4) mirrors. M4 is installed and M3 is about to be installed and aligned.

Howard, Len Seals, Garrett West, and Ron Shiri—all in the Optics Branch of Goddard's Instrument Systems & Technology Division—developed a simplified optical design for an off-axis telescope based on last year's design study with an industrial partner. Delivery of a prototype telescope is expected in April 2015 to support an experimental test program to verify the performance of the design. A separate dedicated test bed to measure the scattered light properties of the tertiary and quaternary mirrors by themselves has been designed and built. Modeling indicates that these two mirrors dominate the scattered light budget, so the test bed allows separate testing of different types of mirror surface roughness and coatings. Diffraction-suppression mask work with Shiri has continued with testing of the fidelity of various mask fabrication technologies. Aaron Spector, a Ph.D. candidate at the University of Florida, just received his degree on mask development as part of an ongoing collaboration with University of Florida Professor Guido Mueller.

Observational Cosmology Laboratory



Dr. Jonathan Gardner
Lab Chief



Dr. Stephen Rinehart
Associate Lab Chief

Laboratory Overview

The Observational Cosmology Laboratory (Code 665) investigates the origin, evolution, contents and ultimate fate of the universe. Scientists seek to understand what powered the Big Bang; the size, shape, and matter-energy content of the universe; when the first stars and galaxies appeared and their evolution over cosmic time; and the nature of the mysterious dark energy that is driving the universe apart. We analyze data from past and current missions to puzzle out the nature of galaxies and the history of the universe and we develop new techniques, new technologies, new cameras and state-of-the-art detectors. The laboratory provides scientific leadership for the James Webb Space Telescope, the Wide-Field Infrared Space Telescope, and for concept studies of other future missions. Other major projects include an upgrade to the High-resolution Airborne Wide-bandwidth Camera (HAWC+) on SOFIA, the balloon-borne Primordial Inflation Polarization Explorer (PIPER), the Balloon Experimental Twin Telescope for Infrared Interferometer (BETTII), the Cosmology Large-Angular Scale Surveyor (CLASS), and the Goddard-IRAM Superconducting 2-Millimeter Observer (GISMO). In addition to the civil servant staff, the laboratory has 49 contract and university scientists, engineers, technicians, post docs, and grad students.

Staff List

Scientist	Research Interest	Project/Mission	Affiliations
Dominic Benford	Astronomical Instrumentation; Galaxy formation and evolution	WFIRST-AFTA HAWC+ BETTII PIPER	Program Scientist (HQ) Institutional Principal Investigator Co-Investigator Co-Investigator
David Chuss	Cosmic microwave background; CMB polarimetry	LAMBDA CLASS PIPER HAWC+	Director Institutional Lead Co-Investigator Co-Investigator
Eli Dwek	Formation and evolution of dust; extragalactic background light; galaxy evolution; supernovae and supernova remnants		

Scientist	Research Interest	Project/Mission	Affiliations
Jonathan Gardner	Galaxy formation and evolution	JWST Euclid ACCESS	Deputy Senior Project Scientist Consortium Member Co-Investigator
Matthew Greenhouse	Astronomical instrumentation, astronomical mission development	JWST	ISIM Project Scientist
Alan Kogut	Cosmic microwave background; far-IR instrumentation; diffuse radio continuum	PIPER PIXIE NASA Scientific Balloon Program	Principal Investigator Principal Investigator Deputy Project Scientist
Jeffrey Kruk	Dark energy; stellar evolution; astronomical instrumentation	WFIRST-AFTA HST ACCESS	Study Instrument Scientist Observatory Project Scientist Institutional Lead
John Mather	Cosmology; astronomical instrumentation	JWST	Senior Project Scientist
Harvey Moseley	Cosmology; astronomical instrumentation	JWST Microshutter Array JWST NIRSpec Science Team PIPER CLASS HAWC+	Principal Investigator Co-Investigator Co-Investigator Co-Investigator Co-Investigator
Susan Neff	Galaxy formation and evolution, nearby galaxies	Cosmic Origins Program	Chief Scientist
Deborah Padgett	Debris disks, star formation	Cosmic Origins Program WFIRST-AFTA	Deputy Chief Scientist Study Scientist
Bernard Rauscher	Astronomical instrumentation, advanced detectors, galaxy formation, cosmology	JWST JWST NIRSpec Detector System JWST NIRSpec Science Team ACCESS WFIRST-AFTA	Deputy ISIM Project Scientist Principal Investigator Co-Investigator Co-Investigator Study Scientist
Jane Rigby	Star-forming galaxies, active galactic nuclei	JWST NuSTAR	Deputy Project Scientist for Operations
Stephen Rinehart	Astronomical instrumentation, interferometry, star and planet formation	TESS BETTII	Project Scientist Principal Investigator
Robert Silverberg	IR astronomy instrumentation	BETTII	Emeritus
George Sonneborn	Supernovae, massive stars	JWST	Project Scientist for Operations
Amber Straughn	Galaxy formation and evolution, communications, education	JWST WFIRST-AFTA	Deputy Project Scientist for Communications Study Scientist

Scientist	Research Interest	Project/Mission	Affiliations
Eric Switzer	Cosmology; astronomical instrumentation	PIPER WFIRST-AFTA	Co-Investigator Study Scientist
Edward Wollack	Astronomical instrumentation, cosmology	NASA Engineering Safety Center ACTpol CLASS HAWC+ GISMO PIPER WFIRST-AFTA	Deputy Chief Scientist Co-Investigator Co-Investigator Co-Investigator Co-Investigator Co-Investigator Study Scientist

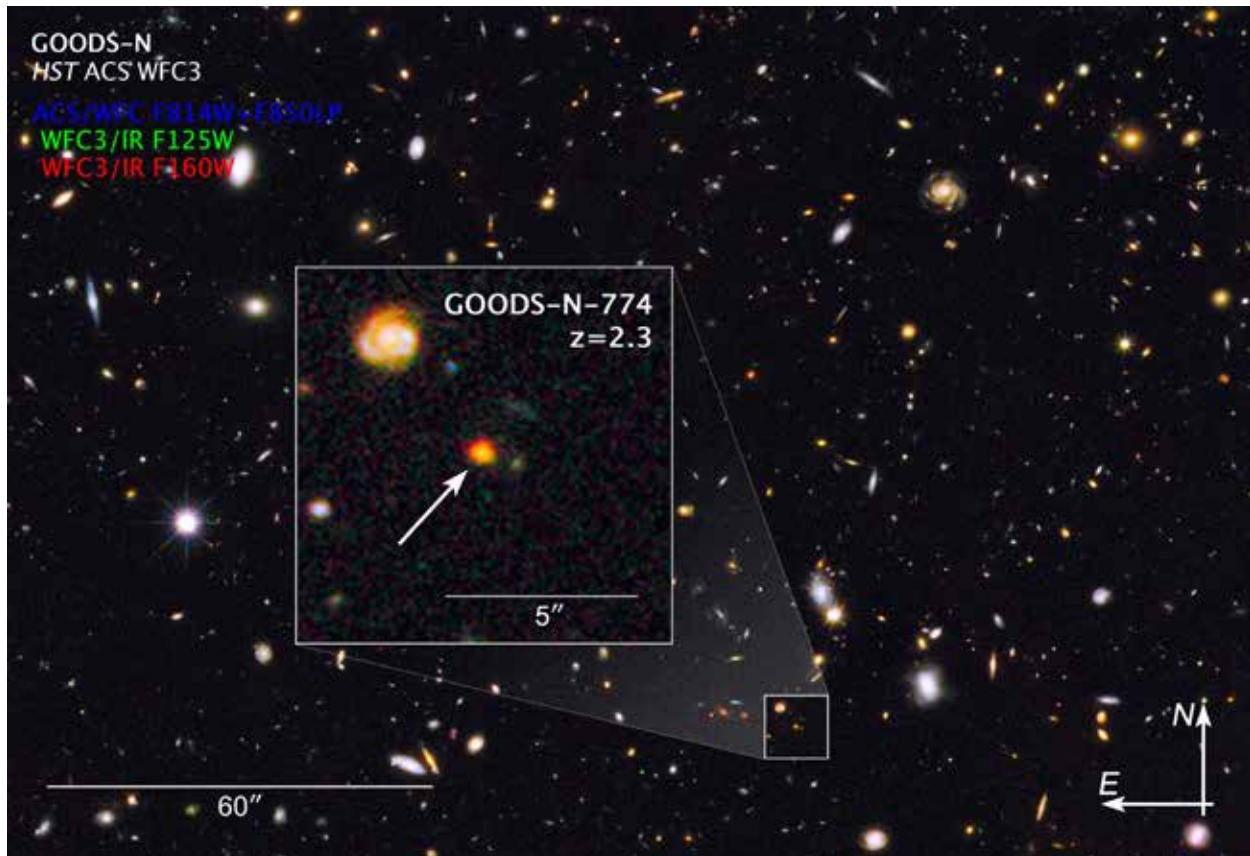
SCIENCE HIGHLIGHTS

A Massive Galaxy in Its Core Formation Phase

Using some of the world's biggest telescopes, Erica Nelson of Yale University has led an international team of astronomers in a search for early versions of the most massive galaxies in the distant universe. Barely two or three billion years after the Big Bang, these young galaxies have already formed upwards

of 100 billion stars, on par with the most massive elliptical galaxies found locally.

There is one significant difference between these distant galaxies and their modern-day counterparts. Although they are similar in terms of their stellar mass, the distant galaxies are far more compact. Imagine taking all of the stars in the Milky Way, spanning 100,000 light-years in diameter, and squashing them into the central bulge, only about 3,000 light-years across.



GOODS-N-774 is a candidate galaxy core in the process of formation, the first one identified exhibiting both stellar structure and the gas dynamics of a forming core.



An artist's impression of a firestorm of star birth deep inside the core of a young, growing elliptical galaxy. Image Credit: NASA, Z. Levay, G. Bacon (STScI)

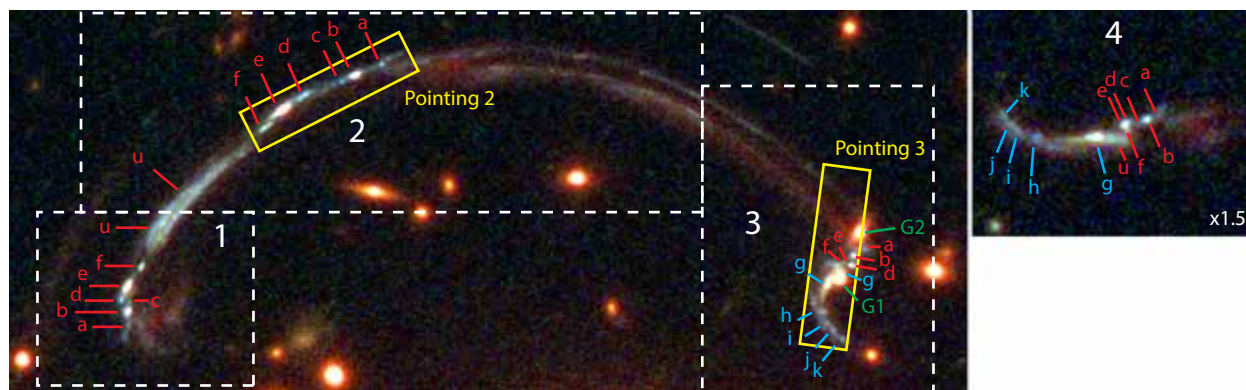
Although we observe dense stellar cores at the hearts of many massive galaxies today, a core in formation has never been observed. Combining data from the Hubble, Spitzer, Herschel and Keck telescopes, new research published in *Nature* reveals the first dense-core galaxy GOODS-N-774 caught in the process of formation. This early galaxy is thought to assemble from the inside out, building up stars in the outskirts during the following 11 billion years.

But the question remains: How do these cores form in the first place? All of the massive cores found so far have already finished their star formation. Several different theories of their construction have been proposed, but astronomers had never seen core formation in progress. The interesting thing about GOODS-N-774 is that while it is both massive and compact, we see that it is still vigorously forming stars at a rate of about 100 new stars per year. At that furious rate, GOODS-N-774 could have formed in as little as a billion years.

If this is how the cores of massive galaxies form, the next big question is why more galaxies such as GOODS-N-774 haven't been found already. One simple idea is that these galaxies form very quickly, making it unlikely we'll catch them in the act. But Nelson and her team, including NASA Postdoctoral

Program Fellow Kate Whitaker, argue instead that galaxies with such strong star formation may be hidden.

These very dense forming cores may contain dust clouds so thick that almost all of their starlight is blocked. GOODS-N-774 does indeed show telltale signs of thermal emission from hot dust at far infrared wavelengths. If this is the case, starlight may not be the best way to find such compact star-forming galaxies. It may be easier to spot infrared light emitted by the dust instead, and this could be the only way to finally figure out when and how the most massive galaxies formed.



The multiply-imaged lensed galaxy RCSGA 032727-132609 as captured by the Hubble Space Telescope's Wide Field Camera 3. Individual star-forming clumps are labeled with red letters. Yellow boxes show where the team obtained OSIRIS/Keck spectroscopy. Credit: Wuyts et al. (2014)

Using Gravitational Lensing to Zoom in on a Distant Galaxy Merger

Astrophysicist Jane Rigby of the Observational Cosmology Laboratory has led a multiwavelength, high spatial resolution study of a spectacular lensed galaxy at redshift 1.70. The multiply-imaged lensed galaxy, designated RCSGA 032727-132609, is young and undergoing a starburst, representative of ultra-violet-selected star-forming galaxies at $z \sim 2$. The lensing magnification resolves spatial scales down to about 300 light-years in the source plane of the galaxy, which allowed the team to pick out individual star-forming regions.

Integral field unit spectroscopy using OSIRIS/Keck reveals disturbed kinematics suggestive of an ongoing interaction and shows a clear signature of a tidal tail. The spectra also show that the star-forming regions are driving winds that vary from region to region.

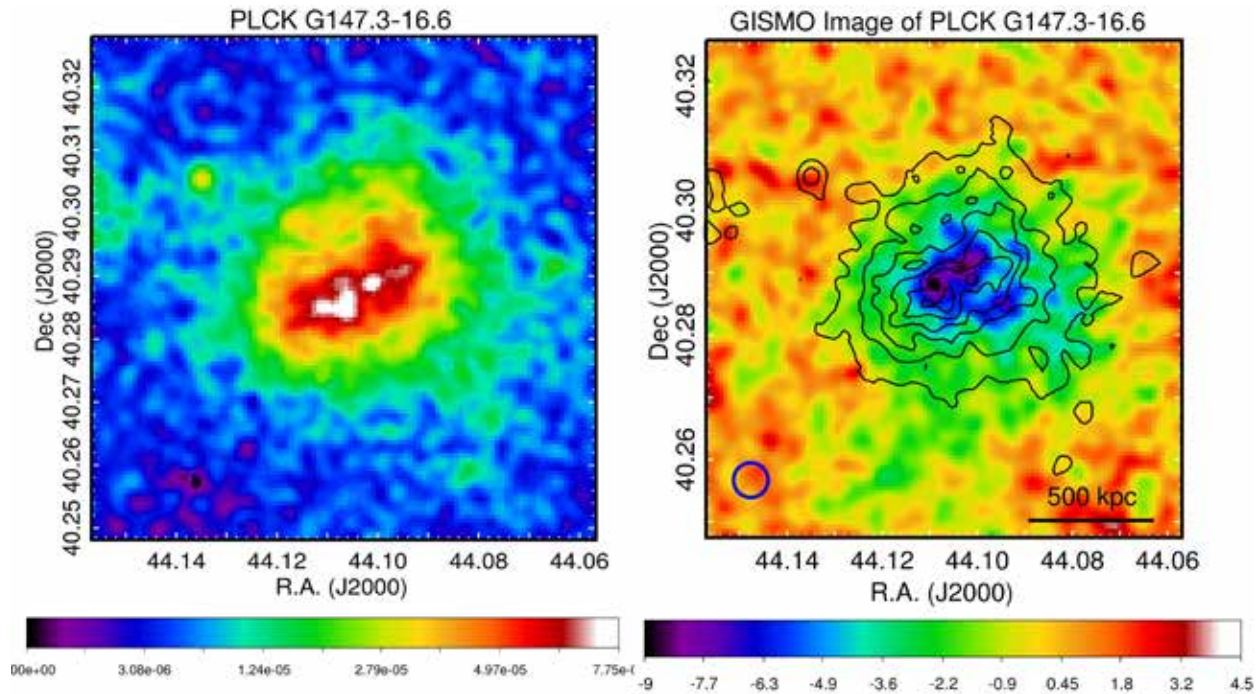
Half the stellar mass in the merger is concentrated in the bright star-forming galaxy, while the other half is concentrated in a UV-faint galaxy that is not forming stars. Thus these observations reveal an equal-mass galaxy merger in progress. The program used guest observer time on the Hubble Space Telescope (PI Rigby) and NASA time on the Keck telescopes (PI Eva Wuyts, Max Planck Institute for Extraterrestrial Physics). The results were published in *The Astrophysical Journal*.

GISMO Reveals Structure of a Distant Galaxy Cluster Merger in Under 5 Hours

Observations of the largest structures present at any given time in the universe allow us to map out how cosmic structure developed and understand the large properties of the universe at the largest scales. Looking back more than 3 billion years ago, the largest clusters we see contain a few thousand galaxies. The Planck satellite, built by the European Space Agency (ESA) with supporting instrument contributions from NASA, recently mapped the entire sky and detected more than 1,200 galaxy clusters and cluster candidates, including more than 560 new discoveries.

One of these previously unknown clusters was the focus of research by a team of scientists using the Goddard-IRAM Superconducting 2-Millimeter Observer (GISMO) on the 30-meter telescope operated by the international Institute of Millimeter Radio Astronomy (IRAM) near Granada, Spain. To the surprise of the team, the ground-based imaging revealed nearly the same structure seen in space-based X-ray observations, but in one-third the time.

GISMO observed the target cluster, called PLCK G147.3-16.6, in April 2014 at 30 times the resolution of the Planck satellite. Both Planck and GISMO took advantage of a phenomenon known as the Sunyaev-Zel'dovich (SZ) effect. Light from the cosmic microwave background (CMB) receives an energy boost when it passes through hot gas in galaxy clusters. On average, high-energy electrons in the gas kick CMB microwaves to higher energies, which creates a "shadow" in the CMB at low frequencies. An important property of the SZ signal is that its strength is



PLCK G147.3-16.6 as imaged by XMM-Newton in X-rays (left) and GISMO SZ imaging (right), with X-ray contours added for ease of comparison.

independent of the cluster's distance, which makes it an important tool for studying cosmic structure.

Early X-ray follow-up observations with ESA's XMM-Newton telescope showed PLCK G147.3-16.6 to be a merger of two smaller clusters. But like all emitted light, X-rays from the cluster's hot gas dims with distance, while the SZ signal does not. As a result, GISMO's first SZ image managed to capture detailed structure in just 4.7 hours.

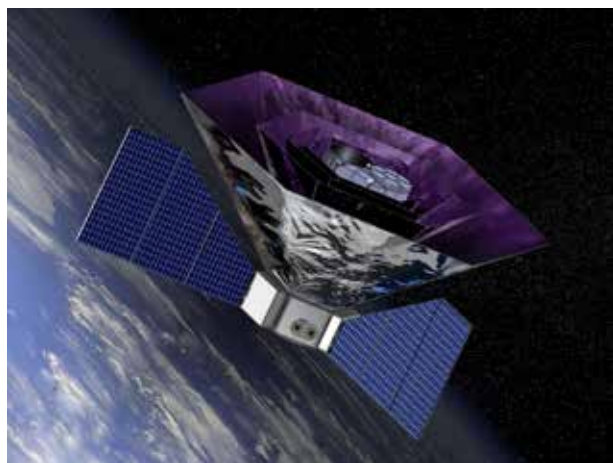
The GISMO SZ observational team is delighted with the results. It includes Tony Mroczkowski (Naval Research Lab), Johannes Staguhn (Johns Hopkins University and ASD), Attila Kovács (Caltech), and Dominic Benford (ASD), with support from several members in Observational Cosmology Lab, including Elmer Sharp, Steve Maher, Ed Wollack, Dale Fixsen, and S. Harvey Moseley. GISMO is an ASD-developed camera operating from a European platform, following an international partnership model.

MISSION AND INSTRUMENT CONCEPTS

Primordial Inflation Explorer (PIXIE)

The advent of a standard model for cosmology is based in part on the concept of inflation, a rapid period of superluminal expansion in the early universe. The exponential growth of the scale size during inflation neatly explains the observed conditions of our universe, but it relies on extrapolation of physics to energies a trillion times beyond those accessible to direct experimentation in particle accelerators. The Primordial Inflation Explorer (PIXIE) will test the inflationary paradigm by searching for the "smoking gun" signature of primordial inflation in the linear polarization of the cosmic microwave background (CMB).

PIXIE is an Explorer mission concept to detect and characterize the signature of primordial inflation. Principal Investigator Alan Kogut leads a team including Goddard co-investigators Eli Dwek, Dale Fixsen, Harvey Moseley and Ed Wollack. PIXIE's innovative design uses a multi-moded "light bucket" and a polarizing Fourier Transform Spectrometer to measure both the linear polarization and spectral energy distribution of the CMB and diffuse astrophysical foregrounds. With spectral coverage span-



Artist's concept of the PIXIE observatory in low Earth orbit.

ning 2.5 decades in frequency (from 30 GHz to 6 THz), PIXIE is uniquely positioned to separate cosmological signals from astrophysical foregrounds based on their different frequency spectra.

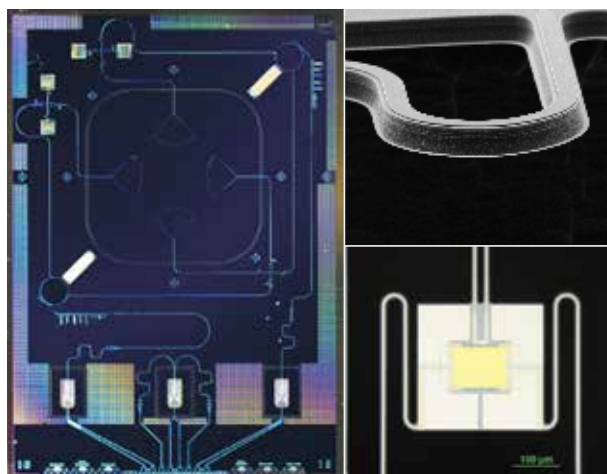
The combination of sensitivity and broad spectral coverage answers exciting questions across cosmic history. PIXIE's primary science goal is the characterization of primordial gravity waves through their signature in CMB polarization. Detection of this gravity wave signal would have profound consequences. It would establish inflation as a physical reality, provide a model-independent determination of the energy scale, and probe physics at energies near Grand Unification (10^{16} GeV). A detection would also provide definitive evidence that gravity is a quantum field and obeys the laws of quantum mechanics, yielding the first observational input to a "final theory" of quantum mechanics and gravity.

PIXIE will also measure the frequency spectrum to search for small distortions from the blackbody spectrum of the CMB. With sensitivity three orders of magnitude better than the seminal COBE/FIRAS blackbody measurements, PIXIE will test astrophysical processes ranging from the nature of the first stars at reionization, to the star-formation history of the universe, and to physical conditions within the interstellar medium of our galaxy.

TECHNOLOGY DEVELOPMENT / SUBORBITAL / BALLOON

Detecting CMB Polarization

Recent advances in observational cosmology suggest the universe underwent a brief period of rapid



Left: A CLASS 40-GHz-detector microwave circuit. Opposite probe antennas (center) couple to a common polarization on the sky once a waveguide and feedhorn are connected. The signal in each polarization is filtered to define the band before thermally coupling to a TES. Right: At top, a scanning electron micrograph image of one of the silicon legs that supports the TES membrane. Below, the rectangle at image center is the TES thermally-isolated membrane.

expansion in its early history. Under this scenario, gravitational waves produced during this inflationary epoch induce a polarization pattern in the cosmic microwave background (CMB) radiation. Detection of the resulting faint signature requires the development and application of polarimeters with high sensitivity, precision control over measurement artifacts, and the use of multiple spectral channels to identify and remove astrophysical foregrounds.

Wollack, Rostem, Chuss (now at Villanova), and Moseley in ASD's Observational Cosmology Laboratory, along with team members Kevin Denis, Thomas Stevenson, and Kongpop U-Yen in Goddard's Applied Engineering and Technology Directorate, are developing detectors for measurement of the polarization of the CMB. These micro-machined silicon sensors are waveguide-coupled and employ Transition-Edge Sensing (TES) bolometers realized on a mono-crystalline silicon substrate. In the sensor concept, radiation from the feedhorn is coupled onto superconducting microstrip circuitry using a planar ortho-mode transducer and subsequently filtered and detected on chip. This and related technologies for characterization of CMB polarization will be demonstrated in the Cosmology Large Angular Scale Surveyor (CLASS) instrument, a project led by Johns Hopkins University to be deployed in Chile's Atacama Desert.



The BETTII team continues to test the control system in the Building 20 High Bay and has demonstrated 1 arcsecond pointing of the entire gondola. The structure and control systems are essentially complete, and over the coming months the external optics and the instrument will be integrated into the full payload.

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII)

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is an 8-meter boom interferometer to operate in the far-infrared (30-90 μm) on a high-altitude balloon. The long baseline will provide unprecedented angular resolution ($\sim 0.5''$) in this band, and the high atmospheric transmission at balloon altitudes will allow the unique double-Fourier instrument on BETTII to obtain spectral resolution up to $R \equiv \lambda/\Delta\lambda \sim 100$. The combination of these capabilities will provide spatially resolved spectroscopy on astrophysically important sources, exploring the physical processes that lurk below the resolution limits of current FIR facilities. The first flight of BETTII, planned for fall 2016, will focus on star-forming clusters, providing powerful new constraints on models of cluster formation.

The BETTII project is now four years old and has made significant progress toward completing the payload. The design of BETTII is complete, and all hardware is either in-hand or has been ordered. The metering truss for the external optics was completed in August 2012; the exoskeleton for electronics and control system components was constructed in summer of 2013; the instrument cryostat has been built and tested; remaining components are all expected by fall 2015. The exoskeleton is currently being used for testing of the gondola control system, including both sensors and control mechanisms, and all individual mechanisms have been carefully

tested under flight-like conditions. Going forward, we are testing individual components of the system and beginning the instrument integration process. By the end of 2015, the entire BETTII payload will be complete, and then the team will focus on the system integration and tests needed to be ready for flight in fall 2016.

Data acquired with BETTII will be complementary to observations with space observatories such as Herschel and the James Webb Space Telescope, exploring the FIR wavelength range with unprecedented high angular resolution. These data will be powerful tools for understanding star formation in clusters, and with future flights, for understanding active galactic nuclei and the late stages of stellar evolution. In addition, the successful flight of BETTII will pave the way for future space interferometry, by validating key technologies and techniques (such as wide-field interferometry). As discussed in the new Astrophysics Roadmap, "Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades," interferometry will play a key role in the future of astrophysics, and BETTII is the first step toward realizing these ambitions.

The BETTII project is a collaboration between Goddard, the University of Maryland, Cardiff University, and University College London, with assistance from the Far-Infrared Telescope Experiment team in Japan. The BETTII team includes ASD scientists Rinehart, Benford, Fixsen, Staguhn, Silverberg (Emeritus), as well as David Leisawitz (Science Proposal Support Office), and Lee Mundy (University of Maryland, College Park). The project also has had contributions from UMCP



The PIPER detector electronics are lowered into a cryostat for testing.

graduate students Maxime Rizzo and Arnab Dhabal and a number of undergraduates from multiple institutions. Information on BETTII interns can be found on the BETTII website (<http://asd.gsfc.nasa.gov/bettii>).

Primordial Inflation Polarization Explorer

The Primordial Inflation Polarization Explorer (PIPER) is a balloon-borne mission to measure the polarization of the cosmic microwave background (CMB) in search of the signature of primordial gravity waves excited by an inflationary epoch in the early universe. Kogut is the PI, and ASD team members include Benford, Chuss, Fixsen, Lazear, Lowe, Mirel, Moseley, Sharp, Staguhn, Switzer, Weston, and Wollack.

PIPER consists of two identical telescopes cooled to 1.5 K within a large (3 meter tall, 3500-liter capacity) liquid helium bucket dewar. There are no windows between the LHe-cooled telescope and the ambient environment—PIPER uses the efflux of boiloff helium gas to prevent the atmosphere at balloon altitudes from condensing on the optics. The unusual cryogenic design provides mapping speed a factor of 10 better than any other CMB instrument,



The PIPER flight dewar is a 3-meter-tall “flying cold tub” containing 3500 liters of liquid helium.

allowing PIPER to achieve sensitivities with overnight balloon flights from New Mexico that would otherwise require 10-day flights from Antarctica.

Each of PIPER’s twin telescopes illuminates a pair of 32×40 element transition-edge superconducting detector arrays for a total of 5120 detectors. A Variable-Delay Polarization Modulator (VPM) injects a time-dependent phase delay between orthogonal linear polarizations to cleanly separate polarized from unpolarized radiation. The combination of background-limited detectors with fast polarization modulation allows PIPER to rapidly scan large areas of the sky. PIPER is the only balloon mission capable of observing on angular scales larger than 20° , where the inflationary signal is expected to be largest.

PIPER will map the sky in both linear and circular polarization, at wavelengths of 1500, 1100, 850, and 500 μm (frequencies 200, 270, 350, and 600 GHz). It will detect the signature of inflationary gravity waves to a factor of three fainter than the lowest value predicted by inflationary models. The unbiased survey of submillimeter polarization will also provide an important probe of interstellar cirrus dust and the large-scale structure of our galaxy’s magnetic field and will be the first sky survey in circular polarization at these wavelengths.

ExoPlanets and Stellar Astrophysics Laboratory



Dr. Karl Stapelfeldt
Lab Chief

Laboratory Overview

The Exoplanets and Stellar Astrophysics Laboratory (Code 667) studies the formation and evolution of stars and planetary systems using advanced telescopes and theoretical techniques. Laboratory staff support both the Hubble Space Telescope and the James Webb Space Telescope projects and are developing new instrument and space mission concepts toward the goal of searching for habitable exoplanets around nearby stars. Key areas of research include exoplanet imaging, studies of protoplanetary and debris disks, ultraviolet astrophysics, and numerical modeling of planetary system evolution. In addition to the civil service staff, the laboratory contains 21 contract scientists, post docs, and graduate students.

Staff List

Scientist	Research Interest	Project/Mission	Role/Affiliation
Richard Barry	Exoplanet microlensing, instrumentation	WIRST-AFTA	Study Scientist
Charles Bowers	Instrumentation	JWST	JWST Deputy Observatory Project Scientist
Kenneth Carpenter	Stellar ultraviolet spectroscopy	HST WFIRST-AFTA	Operations Project Scientist Study Scientist
Mark Clampin	Exoplanetary systems, instrumentation	JWST, TESS	JWST Observatory Project Scientist, TESS mission co-I
William Danchi	Infrared interferometry, exoplanets	LBTI	LBTI science team
Daniel Gezari	Infrared instrumentation	Emeritus	Emeritus
Qian Gong	Optical instrumentation	PISCES	Research Engineer
Theodore Gull	Ultraviolet spectroscopy, massive stars	HST	HST/STIS Deputy PI
Sara Heap	Ultraviolet spectroscopy, exoplanets	HST	HST/COS Science Team
Randy Kimble	Instrumentation	JWST HST	JWST Integration and Test Project Scientist, HST/WFC3 instrument scientist
Marc Kuchner	Circumstellar disk theory, coronagraphy, exoplanets	WFIRST-AFTA Exo-S	Study Scientist Exo-S STDT

Scientist	Research Interest	Project/Mission	Role/Affiliation
Richard Lyon	Coronagraphy, wavefront control, interferometry		Coronagraph technology development
Michael McElwain	Exoplanetary systems, integral field spectroscopy	WFIRST-AFTA Exo-C JWST PISCES instrument	Study Scientist Exo-C STDT JWST Deputy Observatory Project Scientist NASA Roman Tech Fellow
Malcolm Niedner	Cometary plasmas	JWST	JWST Deputy Senior Project Scientist – Technical
Aki Roberge	Circumstellar disk observations, exoplanets	WFIRST-AFTA Exo-S LBTI	Study Scientist Exo-S STDT LBTI Science Team
Karl Stapelfeldt	Circumstellar disk observations, exoplanets	Exo-C LBTI WFIRST-AFTA	Exo-C STDT Chair LBTI Science Team Coronagraph Technologist
Allen Sweigart	Stellar interior modeling		Emeritus
Jennifer Wiseman	Star formation	HST	HST Senior Project Scientist
Bruce Woodgate [†]	Ultraviolet detectors, integral field spectroscopy	HST/STIS PI	Emeritus [†] Deceased 4/29/14

SCIENCE HIGHLIGHTS

A Comet Swarm Around Beta Pictoris

An international team of astronomers including ASD's Aki Roberge uncovered a compact cloud of gas formed by ongoing collisions among a swarm of icy, comet-like bodies around the star Beta Pictoris. The researchers suggest the comet swarm is either the remnant of a crash between two icy worlds the size of Mars or frozen debris trapped by the gravity of an as-yet-unseen planet.

Using the Atacama Large Millimeter Array (ALMA) in Chile, the team mapped submillimeter-wavelength light from dust and carbon monoxide (CO) molecules in a disk surrounding Beta Pictoris. Located about 63 light-years away and only about 20 million years old, the star hosts one of the closest, brightest and youngest debris disks known, making it an ideal laboratory for studying the early development of planetary systems.

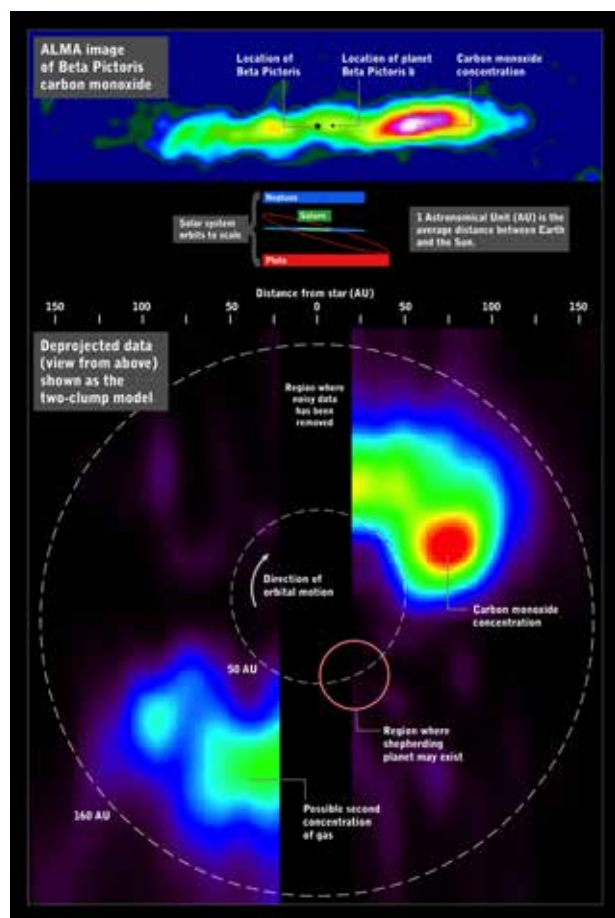
The ALMA images reveal a vast belt of CO located at the fringes of the Beta Pictoris system. Much of the gas is concentrated in a clump located about 13 billion kilometers from the star, nearly three times the distance between Neptune and the sun. The presence of all this gas is a clue that something interesting is going on because the star's ultraviolet light

breaks up CO molecules in about 100 years. In order to offset these losses, the scientists determined that a large comet must be completely destroyed every five minutes. Only an unusually massive and compact swarm of comets could support such an astonishingly high collision rate.

Because we view the disk nearly edge-on, the ALMA data cannot determine whether the CO belt has a single concentration of gas or two on opposite sides of the star. Further studies of the gas cloud's orbital motion will clarify the situation, but current evidence favors a two-clump scenario.

In our own solar system, Jupiter's gravity has trapped thousands of asteroids in two groups, one leading and one following the planet as it travels around the sun. A giant planet located in the outer reaches of the Beta Pictoris system likewise could corral comets into a pair of tight massive swarms. If, however, the gas actually turns out to reside in a single clump, the scientists suggest an alternative scenario. A crash between two Mars-sized icy planets about half a million years ago would account for the comet swarm, with frequent ongoing collisions among the fragments gradually releasing CO gas.

Either way, Beta Pictoris has a fascinating story to tell, and ALMA's keen vision will help astronomers delve ever deeper into the tale.

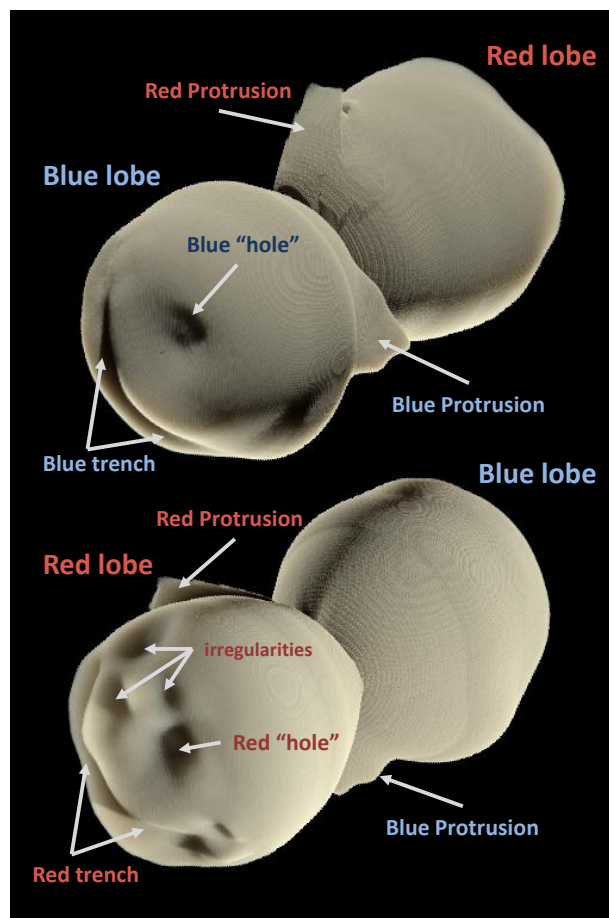


The ALMA image of carbon monoxide around Beta Pictoris (above) can be deprojected (below) to simulate a view looking down on the system, revealing the large concentration of gas in its outer reaches. For comparison, orbits within the solar system are shown for scale. Image Credit: ALMA (ESO/NAOJ/NRAO) and NASA Goddard/F. Reddy

3-D Printing Comes to Astrophysics

ASD's Tom Madura (NPP) and Ted Gull have implemented a novel approach for displaying both astronomical data and computer models as part of their study of Eta Carinae, a massive binary system located about 7,500 light-years away. They have used a 3-D printer to make physical models for understanding the structure of a nebula and the interactions of binary's stellar winds. These models may also serve as teaching tools to help astronomers and the general public understand the phenomena represented.

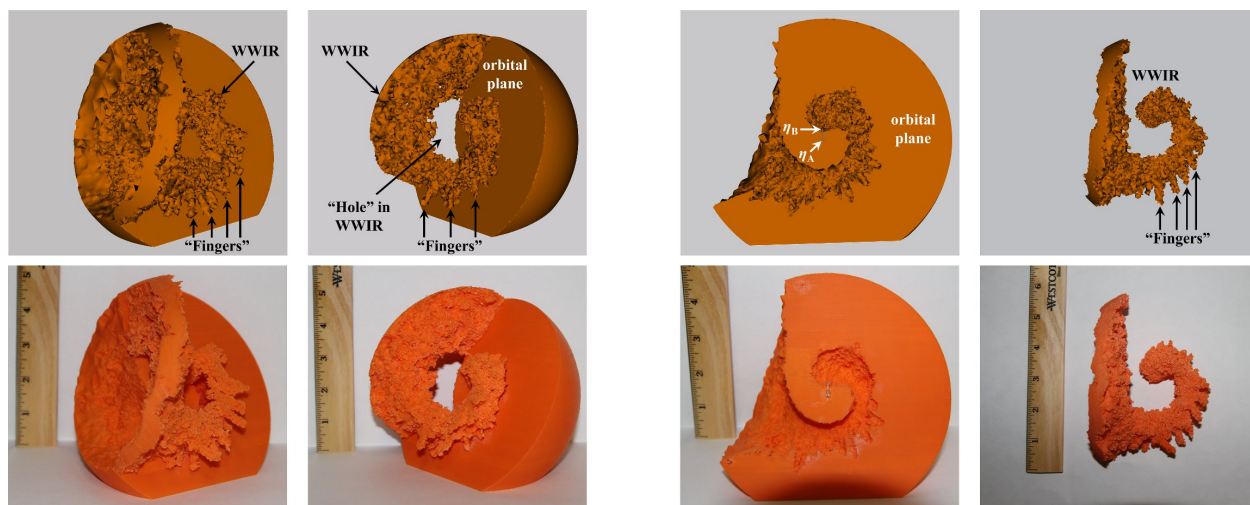
Massive stars are extremely rare compared to stars such as our sun. In our Milky Way galaxy, only a handful of stars with more than 100 solar masses are known. But stars in this mass range were much



Shaded 3-D view of the model Homunculus Nebula. Top: The view from Earth at the top (north is up, east is left). Bottom: A view from the opposite direction (north is down, east is left). Click the image to view the 3-D model (Adobe Reader® required).

more frequent in the early history of the universe and had a huge impact on its evolution. Even among this elite club, Eta Carinae (Eta Car for short) is outstanding, in part due to its beautiful bipolar nebula. Known as the Homunculus Nebula, it was ejected during a near-supernova event called the Great Eruption that occurred in the 1840s.

The Homunculus is a thin, dusty bipolar shell containing at least 10 solar masses and expanding at 600 km/s. Recently, Madura and Gull shared in a study that used spectra with detailed spatial and kinematic information obtained from the European Southern Observatory/Very Large Telescope. When the team displayed the complex data on computer screens, they had trouble understanding the nebula's three-dimensional structure. Finally, the researchers developed a digital 3-D model and printed it using a consumer-grade 3-D printer, making a solid object that could be held and viewed from any



Comparison between the 3-D rendering (top) and the 3-D printed model (bottom) of a simulation of the Eta Car wind-wind interaction at about three months after periastron. Notable features include “fingers” formed by instabilities in the shocked wind-wind interaction region (WWIR) and a “hole” of unshocked primary wind. Click the image to view the 3-D model (Adobe Reader® required).

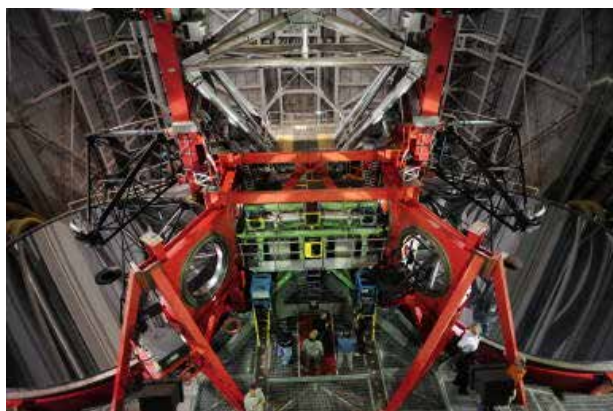
angle. They quickly saw telling small-scale features at the tops of each lobe: a hole, as if a jet-like event punched through the shell, extended grooves, and a tilted pair of wind-like structures. These details led them to conclude that the interaction of the two massive stars had a strong influence on the Great Eruption, but how?

In parallel with the Homunculus studies, Madura and Gull have been developing supercomputer models of the powerful interacting winds of Eta Car’s two massive stars, which are approaching the ends of their stellar lifetimes. Astronomers cannot see either star directly because the winds obscure our line of sight. However, they can monitor X-rays and visible radiation that changes with a 5.52-year period. These observations provide significant clues to the properties of each wind, enabling the researchers to model their interactions.

Two refereed papers on this work, published in *Monthly Notices of the Royal Astronomical Society*, included the novel interactive figures shown here, which allow readers to zoom and rotate to understand these three-dimensional structures. The team went a step further, including in both papers the files needed to print the models using a consumer-grade 3-D printer.

The 3-D prints and visualizations reveal many important, previously unknown structures. The interacting wind models demonstrate significant changes shortly after the stars reach their closest approach, or periastron. Unanticipated small, finger-like structures protrude radially outward from the spiral wind-wind collision region. The team

speculates these fingers are related to instabilities (e.g., thin-shell, Rayleigh-Taylor) at the interface between the radiatively cooled layer of dense post-shock wind from the primary wind and the fast (3,000 km/s) adiabatic post-shock wind from the companion. The easy identification of previously unrecognized physical features highlights the important role visualization and 3-D printing can play in understanding complex 3-D time-dependent simulations of astrophysical phenomena.



The LBTI instrument (green) is mounted between the two LBT primary mirrors.

PROJECTS IN OPERATION

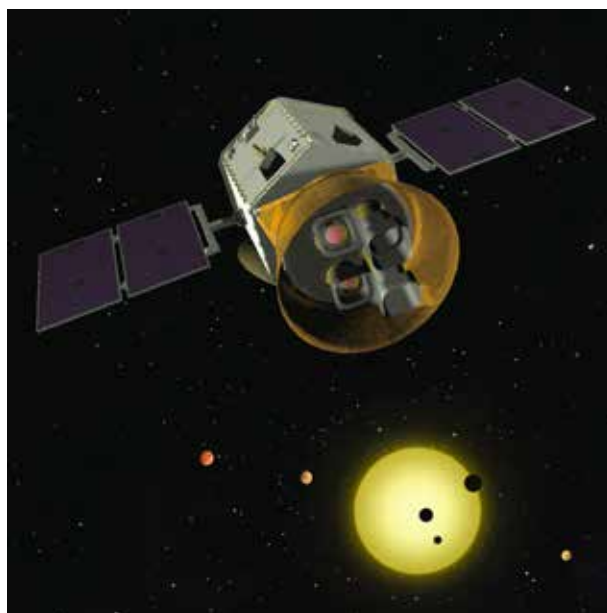
Large Binocular Telescope Interferometer (LBTI)

LBTI is a NASA-funded instrument deployed on the twin 8m telescopes on Mount Graham in Arizona. LBTI operates at 10 μm , nulling out the starlight to reveal any extended emission from warm exozodiacal dust. Dust in the habitable zones of nearby stars is a background noise source against which future missions will detect and characterize Earth-like exoplanets, and thus needs to be measured to define future mission requirements. In 2014, LBTI achieved its first on-sky nulls, encountering telescope vibrations that limited the null stability. Mitigations made during the summer have substantially reduced the problem, with an Operational Readiness review now planned for spring 2015. The LBTI Exozodi Key Science Team published three refereed papers on (1) the first science results for the star Eta Corvi, (2) the target sample selected for the survey, and (3) the modeling strategy for the data from the survey. In Code 667, Danchi, Roberge, and Stapelfeldt are members of the LBTI Exozodi Key Science Team.

PROJECTS IN DEVELOPMENT

Transiting Exoplanet Survey Satellite (TESS)

TESS is an Explorer mission that was selected for development in 2013. Upon its 2017 launch, TESS will conduct a two-year survey searching ~200,000 bright ($V=4-12$), nearby stars for transiting exoplanets. Simulations of the TESS mission predict that TESS will find thousands of new exoplanets,



An artist's concept of TESS in action.

including hundreds of small exoplanets, and even a few (~5) rocky planets in the habitable zones of their host stars. With the time-ordered photometric data for these targets, TESS will provide the target list for future follow-up observations of transiting exoplanets. Because the host stars are bright and nearby, they will be ideal for ground-based observations and well suited to transit spectroscopy with JWST.

In addition, full-frame images from TESS will provide additional scientific return. This includes the detection of ~10,000s of additional exoplanets (largely Jupiter-sized objects), which will help improve the statistical knowledge of the population of exoplanets. It also includes a wide range of non-exoplanet science including studies of white dwarfs, active galactic nuclei, and young stars.

TESS was confirmed to continue into Phase C in October 2014, and the Critical Design Review is scheduled for July 2015. Goddard manages the mission development for mission PI George Ricker at MIT. Code 660 involvement includes Project Scientist Stephen Rinehart and mission science co-Is Rinehart and Mark Clampin.

MISSION AND INSTRUMENT CONCEPTS

Visible Nulling Coronagraph

The Visible Nulling Coronagraph (VNC) is a hybrid coronagraphic/interferometric approach to detecting and characterizing exoplanets. Past results have

included narrowband high contrasts of $5.5 \times 10^{-9} \pm 8 \times 10^{-11}$ at an inner working angle of two optical resolution elements, i.e., $2 \lambda/D$. Research on the ASD VNC testbed has continued throughout 2014 with: (i) the re-design of the mounts for the achromatic phase shifters (APS) and procurement of the APS. These are in the process of mounting and will be subsequently integrated in the testbed to achieve the first broadband VNC milestone. (ii) Delivery and integration of the first 100-percent-yield deformable mirror (DM) and its matching Lyot stop. (iii) The design and tolerancing of the phase-occultation VNC (PO-VNC) and the submission of an FY16 ROSES SAT/TDEM to develop and integrate the PO-VNC. (iv) Advancement of additive manufacturing (3-D printing) as a candidate approach to developing the VNC optical bench with all the mounts manufactured as part of the bench.

The FY14 VNC efforts were primarily concentrated on:

1. Increasing the spectral bandwidth from 1.2 nm to 40 nm and ultimately to >100 nm through the design, fabrication, and assembly of Achromatic Phase Shifters. As part of the FY12/13 SAT, the VNC team designed custom APS that are nearly complete and mounted and will be integrated in the VNC testbed by June 2015 to meet the higher-bandwidth contrast milestone. Brian Hicks (NASA/NPP) with Matt Bolcar (Code 551) and Pete Petrone (Sigma Space) are leading this effort.

2. Delivery and integration of the first 100-percent-yield DM and matching Lyot stop. This work

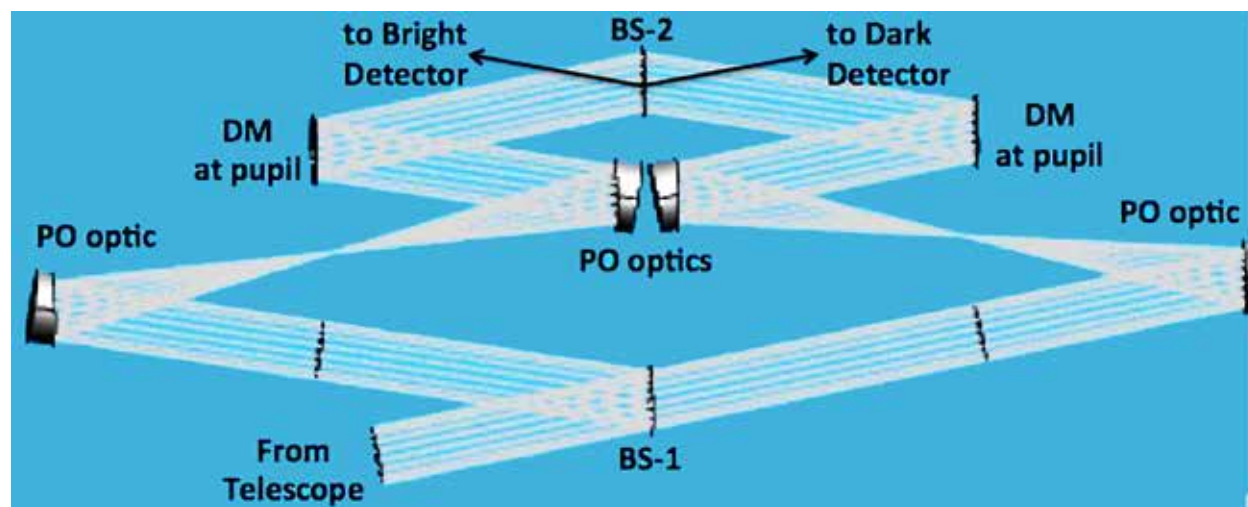
was funded under NASA SBIR funds and was led by Michael Helmbrecht of IRIS-AO. Typically the DM has 3 to 5 failed actuators, requiring masking of this segment in the Lyot stop. This lowers the fidelity of the control and leaks flux into the region of the dark hole. The new DM will alleviate this problem.

3. Advancing the new phase-occultation VNC for segmented aperture telescopes while decreasing the sensitivity to telescope misalignment and instability and increasing the coronagraphic field-of-view. The PO-VNC theoretically allows for ~ 0.6 nulling as opposed to a conventional VNC which requires two nulling interferometers, in series, to achieve only 0.4 nulling. The design, tolerancing and modeling of the PO-VNC optics is funded as an FY14/15 IRAD. A ROSES SAT/TDEM is pending to advance this work further. This work is led by Richard Lyon.

4. Advancement of additive manufacturing (3-D printing) as a candidate approach to developing the VNC optical bench with all the mounts manufactured as part of the bench. FY14 and FY15 work is ongoing to develop a single arm of the VNC using additive manufacturing techniques. This work is led by Tim Stephenson (Materials Engineering Branch) with Brian Hicks (NASA/NPP) and Peter Petrone (Sigma Space).

Exoplanet Probe Mission Study Activities in 2014

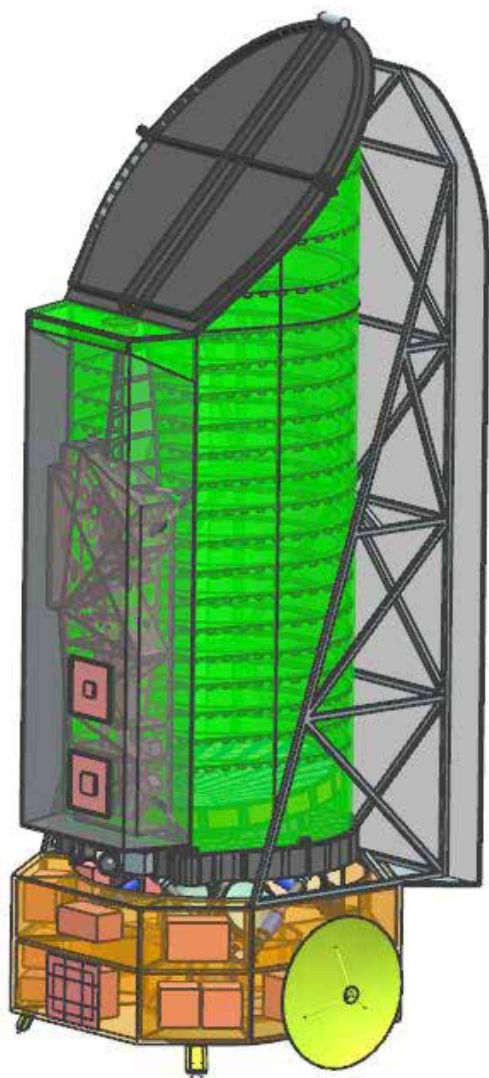
In 2013, the Astrophysics Division at NASA HQ chartered two “probe” mission studies for direct im-



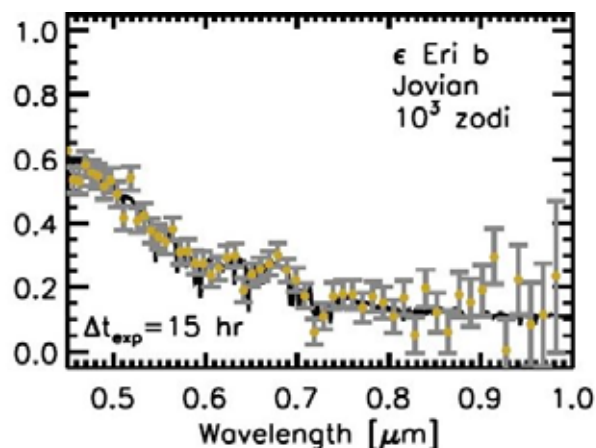
Schematic diagram of the phase-occultation Visible Nulling Coronagraph. Light from a telescope is split (50:50) into two optical paths and recombined at the second beam splitter into two interferometrically combined output channels. One is “bright” and used for control (constructive interference) while the other is “dark” and the science channel. The phase-occultation (PO) optics modify the exit pupil amplitude and phase profile to yield high contrast in a circular region of the science focal plane.

aging of extrasolar planets. Both were challenged to produce mission concepts that accomplished compelling science within a \$1B FY 15 cost cap and to produce final reports by early 2015. Exo-C considered the case of a space telescope with an internal coronagraph, while Exo-S worked a two spacecraft concept consisting of a space telescope and an external starshade. Science and Technology Definition Teams (STDTs) were selected for each study by HQ. Engineering design teams at the Jet Propulsion Laboratory supported each STDT, which included in their membership two scientists from the Exoplanets and Stellar Astrophysics Laboratory.

After several face-to-face meetings and dozens of telecons, the Exo-C and Exo-S final reports are to be



Visualization of the final Exo-C observatory design. The telescope aperture, spacecraft bus, mission orbit, and prime mission lifetime are all comparable to those of Kepler.



Simulated Exo-C spectrum of the giant planet orbiting Epsilon Eridani

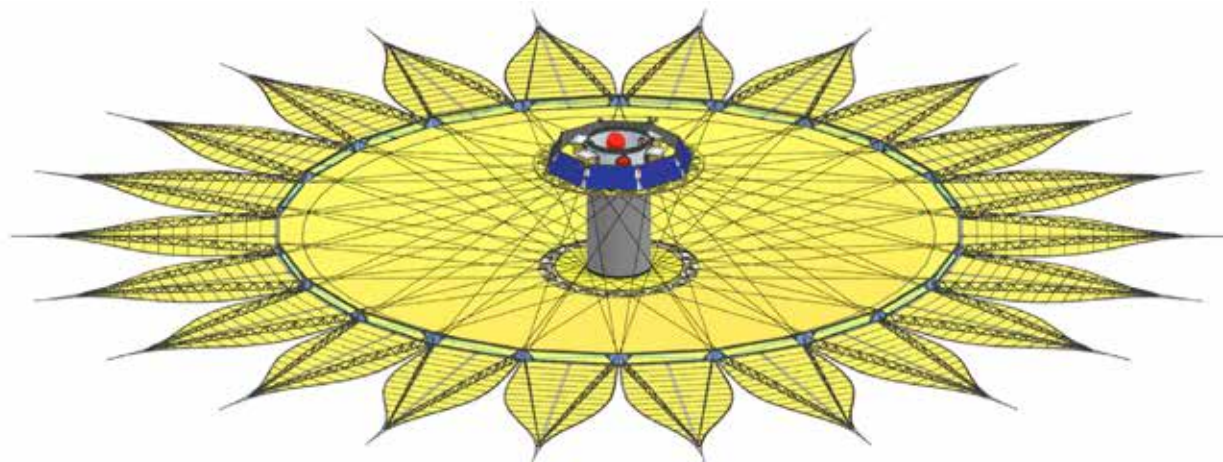
completed in February and March 2015, respectively (see <http://exep.jpl.nasa.gov/stdt/exoc> for the Interim and Final Reports). Exo-C and Exo-S are candidates for the next large NASA astrophysics mission after AFTA/WFIRST. Key design features of these missions should find their way into future mission concepts such as the Habitable Exoplanet Mission that NASA HQ intends to study in the run-up to the Astro2020 Decadal Survey.

Exo-C STDT Activities

The Exo-C STDT was chaired by Karl Stapelfeldt and also included Michael McElwain. The first nine months of the study produced a science case and a technology needs assessment, performed architecture trade studies, and arrived at a baseline design. This work was summarized in an interim report completed in April 2014. During the following 10 months, the STDT and design teams refined the science case; improved the baseline design to reduce mass and cost; conducted a second iteration of coronagraph design and performance evaluation; found



A hypothetical planetary system around the bright star Altair detected by Exo-C in a simulated 12-hour exposure in V, R, and I bands. Shown are Jupiter and Saturn analogs in 5 and 10 AU orbits and a zodiacal dust ring between 2 and 4 AU



A fully deployed starshade: a circular truss surrounded by 22 petals (dedicated mission) or 28 petals (rendezvous mission).

through detailed modeling that the Exo-C configuration would have excellent wavefront stability; produced a detailed technology development plan; and finalized science performance and yield estimates including simulated images and spectra.

The Exo-C final baseline design consists of an unobscured Cassegrain telescope with a 1.4 m primary in an Earth-trailing orbit, designed for a three-year science mission lifetime. It carries a starlight suppression system (SSS) instrument capable of 10^{-9} raw contrast, between 2 and $20 \lambda/D$, between wavelengths of 450 and 1000 nm, and spectral resolution ranging from $R=70$, and consists of the following elements (in optical train order): fine-guidance and low-order wavefront sensor (FGS/LOWFS), wavefront control (WFC) system, coronagraph, an integral field spectrometer (IFS), and an imaging camera. The instrument bench is located on the anti-sun side of the telescope to isolate it from spacecraft disturbances and to provide optimal packaging and polarization performance. The hybrid Lyot coronagraph is baselined for a 2017 project start, primarily because it provides the best demonstrated contrast, bandwidth, and polarization performance to date in testbed experiments on unobscured pupils. The PIAA and vector vortex coronagraphs have the potential to match the hybrid Lyot in these aspects and also provide better throughput and inner working angle performance. They remain options for a later project start. The study's internal cost estimates are in decent agreement with external estimates by the Aerospace Corporation, showing a projected lifecycle cost very close to \$1 B.

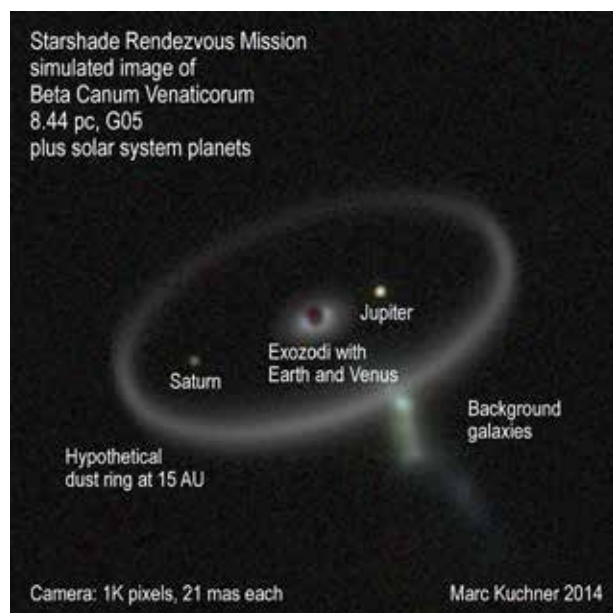
The final Exo-C design would take optical spectra of about a dozen giant planets detected by radi-

al velocity, search more than 100 nearby stars for additional planets beyond the limits of radial velocity detection, take spectra of the brightest newly discovered exoplanets, image structure in hundreds of circumstellar dust disks, and measure the level of exozodiacal light in the habitable zones of more than 100 nearby stars. Planets down to super-Earth and perhaps even Earth sizes would be detectable. Orbits would be determined for newly discovered planets. The mission would yield spectrophotometry of ~ 35 known and new planets and spectra for around half of these.

Exo-S STDT Activities

Roberge, Kuchner and Shawn Domagal-Goldman (Planetary Environments Laboratory) served on the Exo-S STDT, which was chaired by Sara Seager (MIT). The Starshade mission combines two spacecraft—a telescope and starshade—aligned to suppress light from exoplanet host stars and detect and characterize a range of different kinds of exoplanets. This approach offers several advantages, including inherently broadband images, an outer working angle limited only by detector size, and the ability to detect Earth-size planets even with a small telescope aperture.

The contrast of starshade missions is limited by manufacturing and deployment errors, thermal deformations and formation flying errors; this study assumed a contrast of 4×10^{-11} as a design goal. The missions studied by the Exo-S team would all characterize about a dozen known gas giant planets at a spectral resolution of $R=70$, like the Exo-C mission. But the intrinsically high contrast of this method



Simulation of an Exo-S rendezvous mission image of a solar-system-like planetary system orbiting a nearby sun-like star. The image is a composite of three bands (510, 658, 825 nm), square-root scaled and mapped to blue, green, and red to create a false-color image. The Jupiter and Saturn twins are easy to recognize, and the Venus twin in this system is detected at a signal-to-noise ratio of about 12. The model for background galaxies was generated with the Illustris cosmological simulation (Vogelsberger et al. 2014) converted to mock images using stellar population synthesis models (Torrey et al. 2014) Credit: Gregory Snyder, STScI

also allows them to reach beyond giant planets into the range of super-Earths and even Earth analogs.

Like the Exo-C team, the Exo-S team began by honing a single baseline mission, a starshade combined with a dedicated 1.1m telescope, and described this concept in an interim report completed in April 2014. Subsequently, the team added a new configuration to the trade study: a “rendezvous” mission that combines the starshade with the AFTA WFIRST telescope to harness its larger aperture. The Exo-S “dedicated” mission uses a commercial 1.1 m telescope in a heliocentric, Earth-leading driftaway orbit plus a 30 m diameter starshade. The “rendezvous” mission utilizes the WFIRST AFTA 2.4m in an L2 halo orbit plus a 34 m diameter starshade. The rendezvous mission offers integration times that are lower by a factor of 10, allowing more planets to be characterized during the mission.

The Exo-S team estimated the cost of the dedicated mission to be slightly more than \$1 billion, in good

agreement with independent cost estimates. But the more powerful “rendezvous” mission, a starshade to be combined with WFIRST AFTA, yielded a cost estimate of roughly \$600 million. DRM simulations predict that this “rendezvous” mission would detect roughly two habitable-zone Earth analogs. This mission would benefit from a dedicated instrument on WFIRST AFTA to take advantage of the starshade’s large bandwidth, but could also utilize the WFIRST AFTA coronagraphs’s IFS with minimal modification to the current design

TECHNOLOGY DEVELOPMENT

Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies (PISCES)

Development of a high-contrast optical integral field spectrograph was initiated in mid-2013 when McElwain was selected as a NASA Roman Technology Fellow. PISCES is being integrated and tested at Goddard this year and will be delivered to the JPL High Contrast Imaging Testbed in early 2016. Since the Roman selection, the AFTA implementation of WFIRST was equipped with a Coronagraph Instrument (CGI). PISCES was folded into the CGI technology development program and now represents the prototype flight science camera for AFTA-CGI and is expected to fly on a future New Worlds exoplanet imager. PISCES will demonstrate technical readiness for this instrument type and serve as a diagnostic tool for broad-band coronagraphy.

UV Photon-counting Detector Development

Norton, Stock, and Hilton are developing a high quantum efficiency (QE, >70 percent), very low noise electron-bombarded CMOS (EBCMOS) detector for ultraviolet (100–300 nm) space-based imaging and spectroscopy. Existing detectors such as the STIS MAMAs flown aboard the Hubble Space Telescope, while providing otherwise excellent performance characteristics, exhibit low QE (<10 percent). There is therefore considerable room for improvement in the performance of these crucial detector systems. Development of high QE, very low noise photon-counting detectors for UV wavelengths has been identified as a very high priority

by the Cosmic Origins (COR) Program Office annual technical report for future planned missions such as LUVOIR.

Significant progress has so far been made toward this goal at ASD with the development of gallium nitride photocathodes, with quantum efficiency of > 70 percent already demonstrated in the far-UV (Lyman alpha, 121 nm). Our current activities include extending this high QE over a wavelength range limited by the band-gap cutoff of the material. Recently we have identified, procured and begun activation of modulated band gap heterostructured GaN material from SVT Inc. that demonstrates QE > 70 percent at 250nm.

In addition, we have demonstrated excellent photon-event readout characteristics, employing a back-thinned $1.6K \times 1.2K$ CMOS sensor with excellent pulse height distribution, efficient noise discrimination and imaging characteristics with PSF (FWHM) < 15 microns. Future plans include increasing the imaging format. To meet this objective, we will procure a $2K \times 2K$ array (single sensor) and camera from NRL that is very similar to the camera used for their upcoming SohoHi mission scheduled for launch in 2017. This has the added advantage in that camera and sensor are flight-qualified. This device can be stitched and mosaicked into a $4K \times 4K$ imaging format using four of the $2K \times 2K$ sensors, or an $8k \times 2k$ pixel spectroscopic format.

Tim Norton (UMBC) has taken over leadership of this effort due to the passing of Bruce Woodgate, the original project PI. Karl Stapelfeldt is serving as administrative PI

Community Outreach: Disk Detective

This year, ASD astronomers invited the public to help them discover planetary systems through a new website, DiskDetective.org. At DiskDetective.org, volunteers view data from NASA's Wide-field Infrared Survey Explorer (WISE) mission and three other surveys.

WISE measured more than 745 million objects, representing the most comprehensive survey of the sky at mid-infrared wavelengths ever taken. Among these objects are thousands of planetary systems, recognizable by the dusty disks that surround them, waiting to be discovered. But galaxies, interstellar dust clouds and asteroids also glow in infrared, which stymies automated efforts to identify these disks. The volunteers at Disk Detective.org find the



Images of these disks made by larger telescopes often reveal beautiful patterns, as seen here with HD 181327. The dusty ring likely is sculpted by an extrasolar planet. Credit: NASA, ESA, G. Schneider (U. of Arizona), HST/GO 12228 Team.

disks by watching 10-second videos of objects seen by WISE and classifying them by clicking on a selection of buttons on their screens.

In less than a year, citizen scientists using DiskDetective.org logged 1 million classifications of potential debris disks and disks surrounding young stellar objects (YSO disks). Volunteers even made their own tutorial videos for the project and translated the website into 10 different languages. The project won a ROSES ADAP grant and was featured on the White House blog.

All this work so far has yielded 478 objects of interest, of which 240 have been reobserved with ground-based telescopes in Arizona, New Mexico, California, and Argentina. The best of these disk candidates, in turn, will become targets for larger ground-based telescopes, and, down the line, Hubble and/or JWST. The Disk Detective science team, led by Kuchner and including McElwain and Nesvold, hopes to complete the project by 2018, when JWST launches. But many objects are waiting to be classified and many disks are waiting to be discovered, so please come to DiskDetective.org and join the search.



Citizen science in action with Disk Detective. Credit: NASA's Goddard Space Flight Center

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